# Rare Kaon Decays

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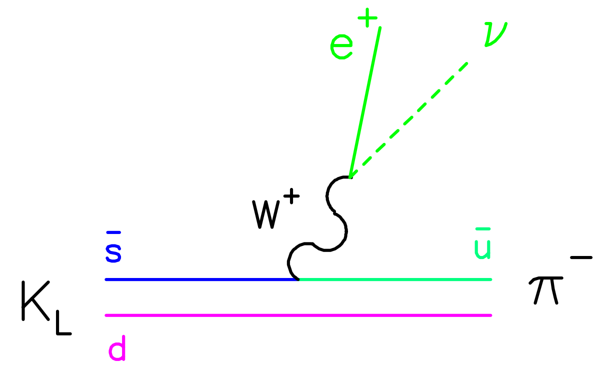
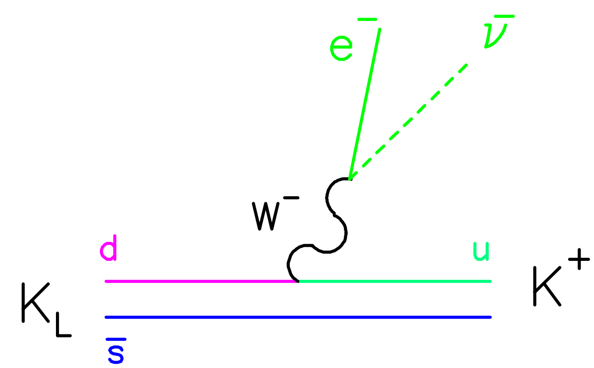
SLAC/LBL 6 Sept 2001

# What makes decays rare?

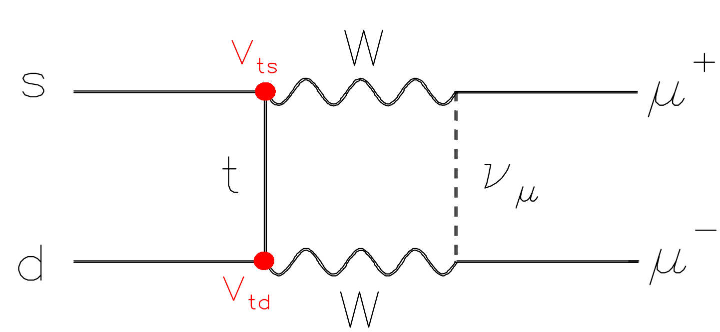
Common decay:




Rare by virtue of kinematics:




Rare since suppressed to 2nd order:



# Motivation for Rare $K$ Decay Experiments

## Forbidden

S.M. forbids (or greatly inhibits) many kinematically possible modes

A number of these are allowed (or enhanced) by alternative approaches

Accessible sensitivity to these processes corresponds to very high mass scales

## Discouraged

Certain very inhibited processes cleanly sensitive to S.M. parameters

## Tolerated

Suppressed processes are a good area for testing chiral perturbation theory and other approaches to understanding the low energy structure of the S.M.

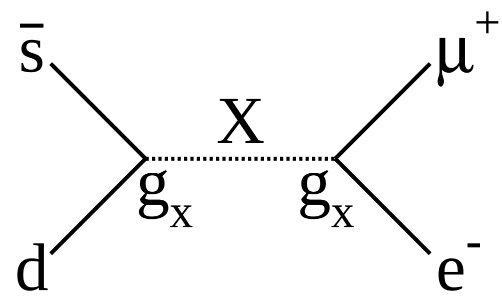
# Rare $K$ decay modes studied recently

$K^+ \to \pi^+ \nu \bar{\nu}$
$K_L \to \pi^0 \mu^+ \mu^-$
$K^+ \to \pi^+ \mu^+ \mu^-$
$K_L \to \mu^+ \mu^-$
$K^+ \to \pi^+ e^+ e^- \gamma$
$K_L \to e^\pm e^\mp \mu^\pm \mu^\mp$
$K_L \to \pi^+ \pi^- \gamma$
$K^+ \to \pi^+ \pi^0 e^+ e^-$
$K_L \to \pi^0 \gamma \gamma$
$K^+ \to \mu^+ \nu \gamma$
$K^+ \to \mu^+ \nu e^+ e^-$
$K_L \to e^+ e^- \gamma$
$K_L \to e^+ e^- \gamma \gamma$
$K_L \to e^+ e^- e^+ e^-$
$K^+ \to \pi^+ \mu^+ e^-$
$K_L \to \mu^\pm e^\mp$
$K^+ \to \pi^- e^+ e^+$
$K^+ \to \pi^+ X^0$
$K^+ \to \pi^+ \gamma$

$K_L \to \pi^0 \nu \bar{\nu}$
$K_L \to \pi^0 e^+ e^-$
$K^+ \to \pi^+ e^+ e^-$
$K_L \to e^+ e^-$
$K^+ \to \pi^+ \pi^0 \nu \bar{\nu}$
$K^+ \to \pi^+ \pi^0 \gamma$
$K_L \to \pi^+ \pi^- e^+ e^-$
$K^+ \to \pi^0 \mu^+ \nu \gamma$
$K^+ \to \pi^+ \gamma \gamma$
$K^+ \to e^+ \nu e^+ e^-$
$K^+ \to e^+ \nu \mu^+ \mu^-$
$K_L \to \mu^+ \mu^- \gamma$
$K_L \to \mu^+ \mu^- \gamma \gamma$
$K_L \to \pi^0 e^+ e^- \gamma$
$K_L \to \pi^0 \mu^\pm e^\mp$
$K^+ \to \pi^- \mu^+ e^+$
$K^+ \to \pi^- \mu^+ \mu^+$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$

# Lepton Flavor Violation

Poster child for sensitivity to BSM processes such as $\longrightarrow$ Attainable sensitivity corresponding to $M_X \gtrsim 100$TeV, clean signatures




Most BSM theories predict *some* LFV in $K$ decays:
- extended technicolor
- SUSY
- heavy neutrinos
- horizontal gauge bosons

Necessary to study both two and three body decays
- check Lorentz structure of any new interaction
- generation number sensitivity

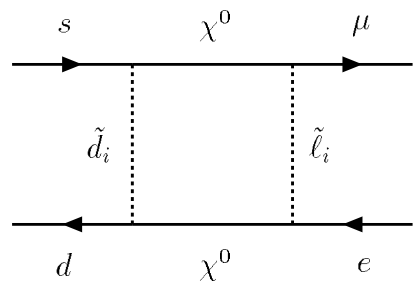
Current status:

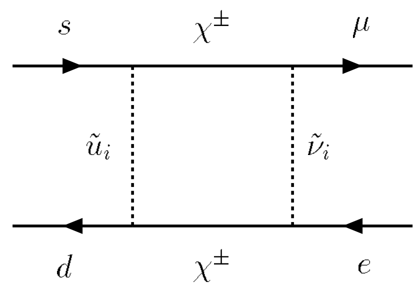
| Process | 90% CL Limit | Experiment | Reference |
|---|---|---|---|
| $K_L \to \mu e$ | $4.7 \times 10^{-12}$ | AGS-871 | PRL 81:5734 |
| $K^+ \to \pi^+ \mu^+ e^-$ | $2.8 \times 10^{-11}$ | AGS-865 | PRL 85:2450 |
| $K^+ \to \pi^+ \mu^- e^+$ | $5.2 \times 10^{-10}$ | AGS-865 | PRL 85:2877 |
| $K_L \to \pi^0 \mu e$ | $4.4 \times 10^{-10}$ | KTeV | Bellantoni/Moriond |

More $K^+ \to \pi^+ \mu^+ e^-$ and $K_L \to \pi^0 \mu e$ data under analysis.

# LFV in SUSY

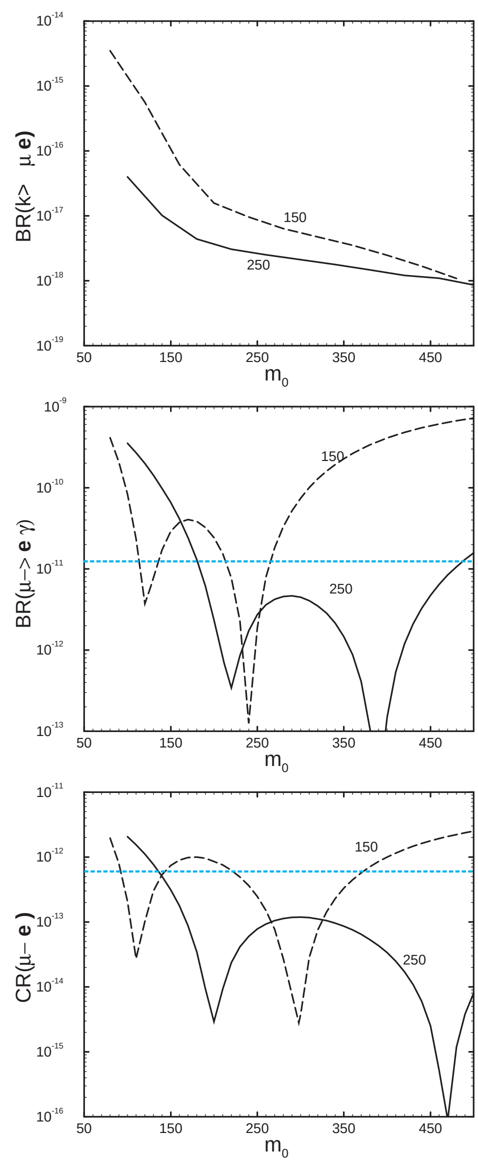
Lepton flavor violation in $K$ decay is allowed in the MSSM by diagrams like those at right (See A. Belyaev *et al.*, hep-ph/0008276.



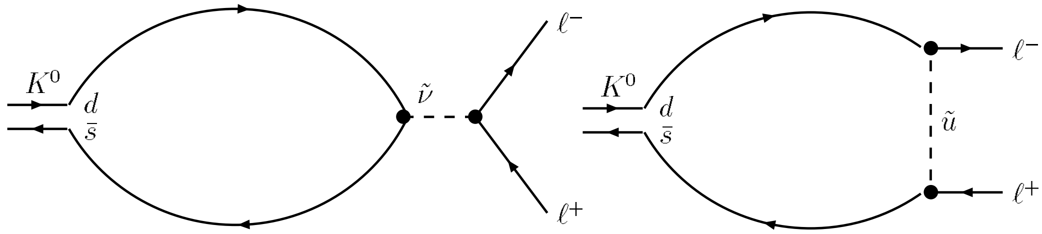

But the rate from such diagrams is very suppressed with respect to current experimental senstivity. The effects in $K$ decay are also suppressed relative to those in rare muon processes such as $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion in the field of a nucleus

This can be seen in the plots at right which show the predictions for $K_L \to \mu e$, $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion assuming the same values of SUSY parameters ($\mu < 0$, $tan\beta = 20$, $m_{1/2} = 150$ & $250\,\mathrm{GeV}$, vs $m_0$). The dotted horizontal lines indicate the current upper limits on $\mu \to e\gamma$ and $\mu^- \to e^-$ conversion. There are proposals to push the sensitivity of both muon processes by more than three orders of magnitude.



# LFV in SUSY-2

Once R-parity is relaxed, LFV effects in SUSY can be large:




*Quark/sfermion diagrams involving R-violating couplings that yield $K^0 \to \ell^\pm \ell^\mp$ decays.*

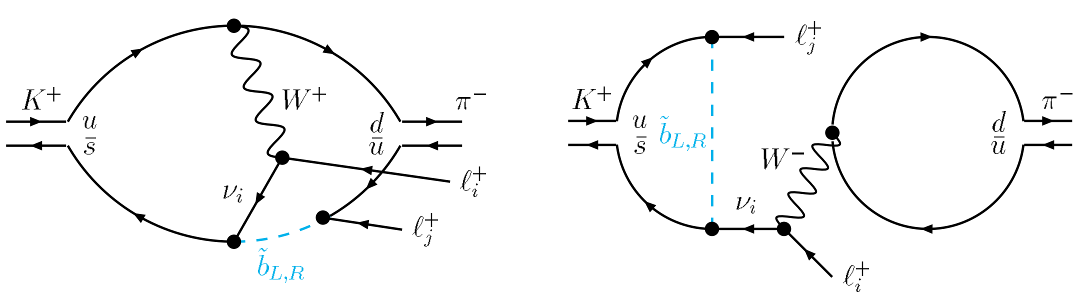
Current LFV data itself gives strictest limits on the couplings.

*e.g.* $B(K_L \to \mu e) < 4.7 \cdot 10^{-12}$ gives -

$$\lambda_{i21}\lambda'_{i12} \text{ and } \lambda_{i12}\lambda'_{i21} \leq 6.2 \cdot 10^{-9} \times (\frac{m_{\tilde{\nu}}}{100\text{GeV}})^2$$

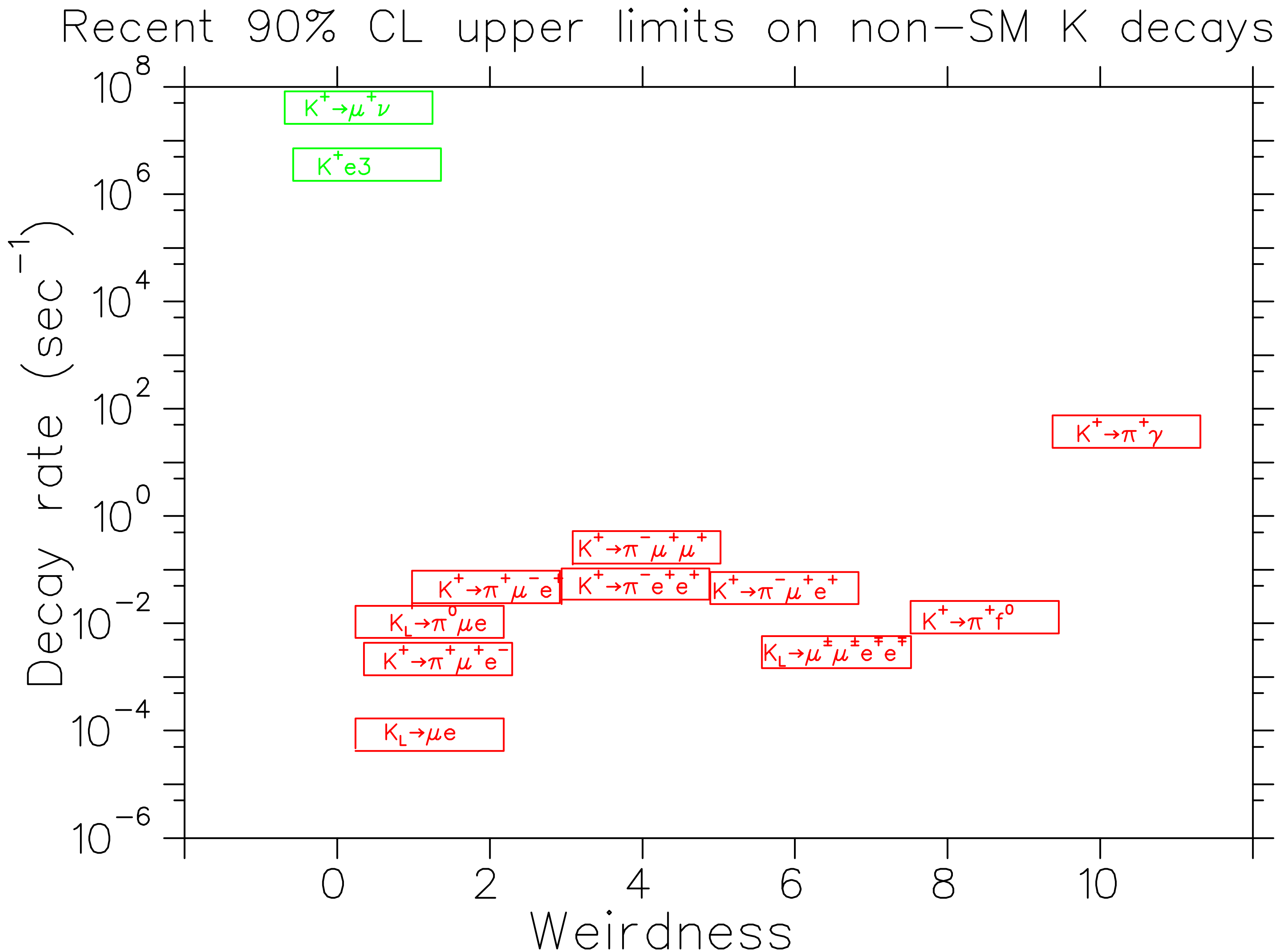
$$\& \qquad \lambda'_{2i1}\lambda'_{1i2} \text{ and } \lambda'_{1i1}\lambda'_{2i2} \leq 1.9 \cdot 10^{-7} \times (\frac{m_{\tilde{\mu}}}{100\text{GeV}})^2$$

SUSY can also give like-sign lepton decays like $K^+ \to \pi^- \mu^+ e^+$ through $\tilde{b}$ mixing, *e.g.*:




However the senstivity for these is much reduced.
Even setting the $\tilde{b}$ mixing matrix element to 1,
current limit $B(K^+ \to \pi^- \mu^+ e^+) < 5 \cdot 10^{-10}$ would give -

$$\lambda'_{2k2}\lambda'_{11k} \leq 10 \times (\frac{m_{\tilde{d}_k}}{100\text{GeV}})^2$$

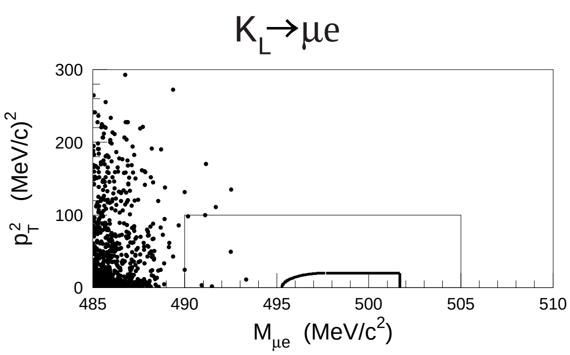


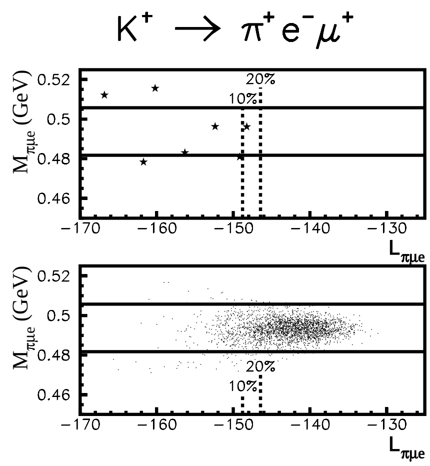
Recent 90% CL upper limits on non−SM K decays
Decay rate (sec$^{-1}$)
Weirdness
$10^{8}$
$10^{6}$
$10^{4}$
$10^{2}$
$10^{0}$
$10^{-2}$
$10^{-4}$
$10^{-6}$
0
2
4
6
8
10
$K^{+}\rightarrow\mu^{+}\nu$
$K^{+}e3$
$K^{+}\rightarrow\pi^{+}\gamma$
$K^{+}\rightarrow\pi^{-}\mu^{+}\mu^{+}$
$K^{+}\rightarrow\pi^{+}\mu^{-}e^{+}$
$K^{+}\rightarrow\pi^{-}e^{+}e^{+}$
$K^{+}\rightarrow\pi^{-}\mu^{+}e^{+}$
$K_{L}\rightarrow\pi^{0}\mu e$
$K^{+}\rightarrow\pi^{+}f^{0}$
$K_{L}\rightarrow\mu^{\pm}\mu^{\pm}e^{\mp}e^{\mp}$
$K^{+}\rightarrow\pi^{+}\mu^{+}e^{-}$
$K_{L}\rightarrow\mu e$

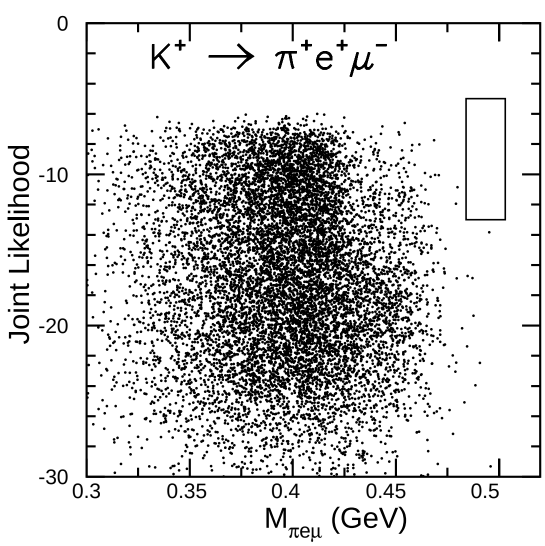
# Prospects for LFV

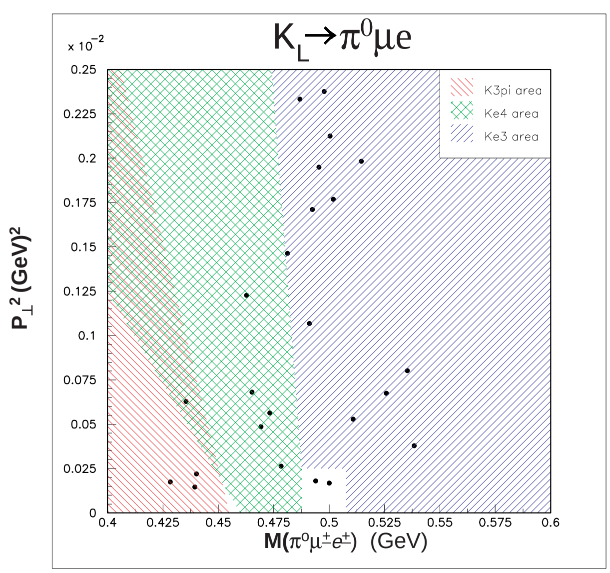
Current experiments have already helped kill the most promising approaches that predicted finite effects. Theorists now predicting more accessible levels of LFV in rare muon processes.

Future progress on LFV in kaon decays likely to be slow. No dedicated experiments on the near horizon, and background getting harder to fight:



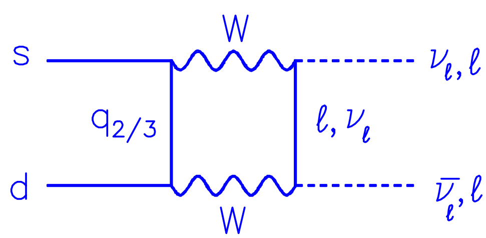



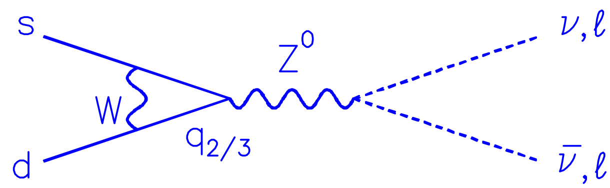



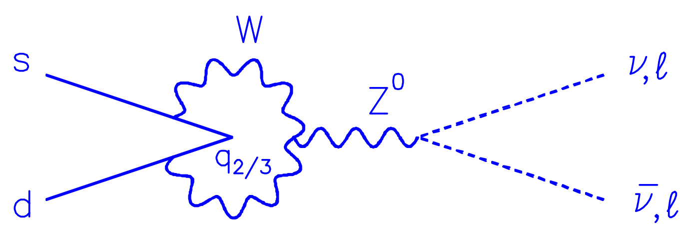

Probably no significant progress at least until JHF or other new facility turns on.

# One-loop $K$ Decays

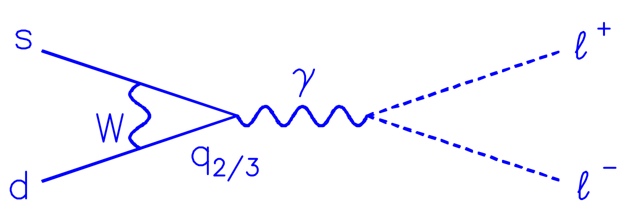
Short-distance contributions to $K$ decays. These decays include $K_L \to \pi^0 \nu\bar{\nu}$, $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$, $K_L \to \pi^0 \mu^+\mu^-$, etc. The hadronic matrix elements involved are known from common decays such as $K^0 \to \pi^+ e^- \bar{\nu}$. These contributions can be cleanly calculated in terms of $m_t$, $m_c$ and the product of CKM elements $V_{ts}^* V_{td} \equiv \lambda_t$.




But there's a Murphy's Law for these processes:
The same interactions that allow charged final state leptons to be detected, mediate long-distance contributions. E.g.:




To avoid this one must exploit decays containing a $\nu\bar{\nu}$ pair.

# $\underline{K^+ \to \pi^+ \nu \bar{\nu}}$

$V_{ts}^* V_{td}$

$$B\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = \frac{r_{K^+} \alpha^2 B\left(K^+ e3\right)}{V_{us}^2 2\pi^2 sin^4\theta_W} \sum_l \left| \lambda_c X_{NL}^{\ell} + \lambda_t X\left(x_t\right) \right|^2 \approx 10^{-10}$$

contains QCD corr.
has been calc'd to NLLA

$X \approx 1.57 \left(m_t/170\right)^{1.15}$

$$= 4.1 \times 10^{-11} A^4 X^2\left(x_t\right) \left[\bar{\eta}^2 + \frac{2}{3}\left(\rho_o^e - \bar{\rho}\right)^2 + \frac{1}{3}\left(\rho_o^\tau - \bar{\rho}\right)^2\right]$$

where $\rho_o^\ell \equiv 1 + \frac{X_{NL}^\ell}{A^2 \lambda^4 X(x_t)}$; $r_{K^+} = 0.9$

calc. uncertainty only a few %

In leading order in Wolfenstein parameters,
$B\left(K^+ \to \pi^+ \nu \bar{\nu}\right)$ determines a circle in the $\rho$, $\eta$ plane with
center $\left(\rho_o, 0\right)$; $\rho_o \equiv \frac{2}{3}\rho_o^e + \frac{1}{3}\rho_o^\tau \approx 1.4$ and radius $\approx \frac{1}{A^2}\sqrt{\frac{B(K^+ \to \pi^+ \nu \bar{\nu})}{10^{-10}}}$

Don't need to deal with Wolfenstein parameters, instead:

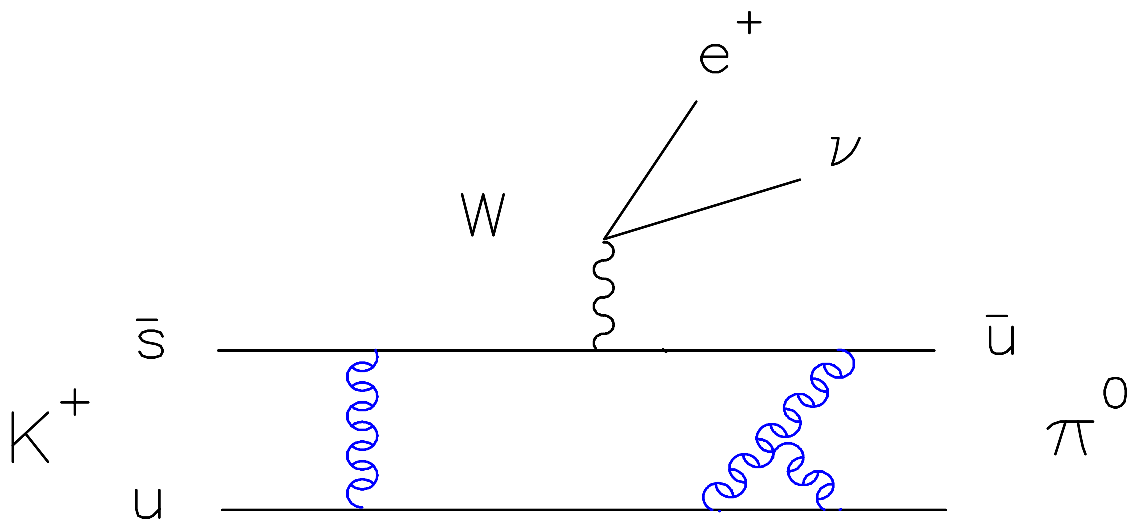
$$B\left(K^+ \to \pi^+ \nu \bar{\nu}\right) = .00015\left[\left(\lambda_c \bar{X} + Re\left(\lambda_t\right) X\left(x_t\right)\right)^2 + \left(Im\left(\lambda_t\right) X\left(x_t\right)\right)^2\right]$$

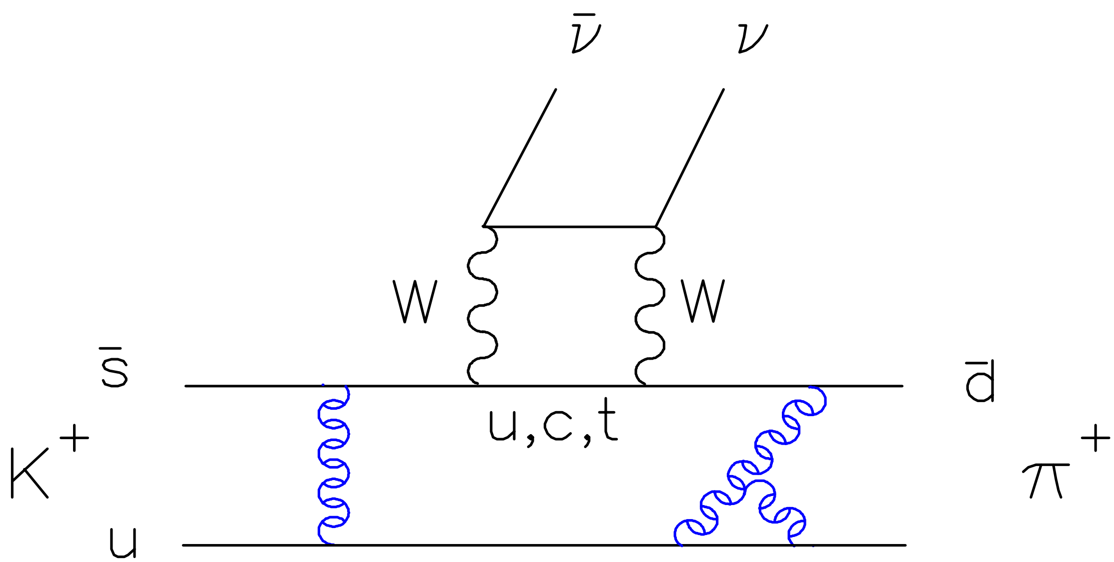
where $\bar{X} \equiv \left(2X_{NL}^e + X_{NL}^\tau\right)/3$

This gives a circle in the $Re\left(\lambda_t\right)$, $Im\left(\lambda_t\right)$ plane

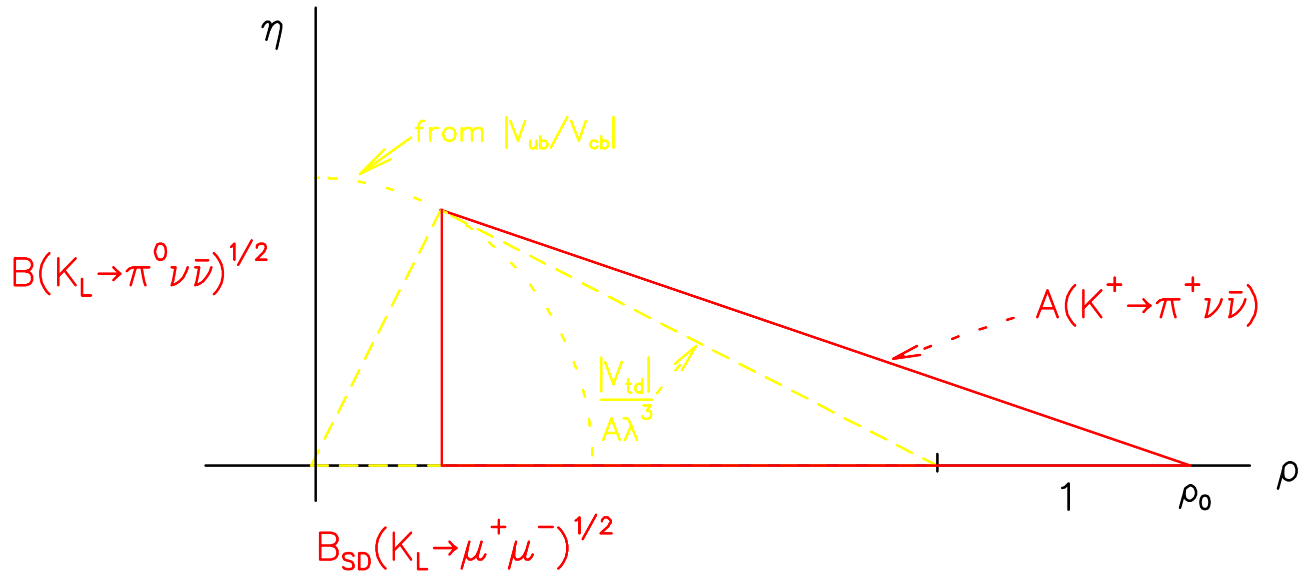
From measurement of $B = \left(K^+ \to \pi^+ \nu \bar{\nu}\right)$, can get limits
(tangents to circle)

# K Hadronic Matrix Element



# Rare K Decay and the Unitarity Triangle



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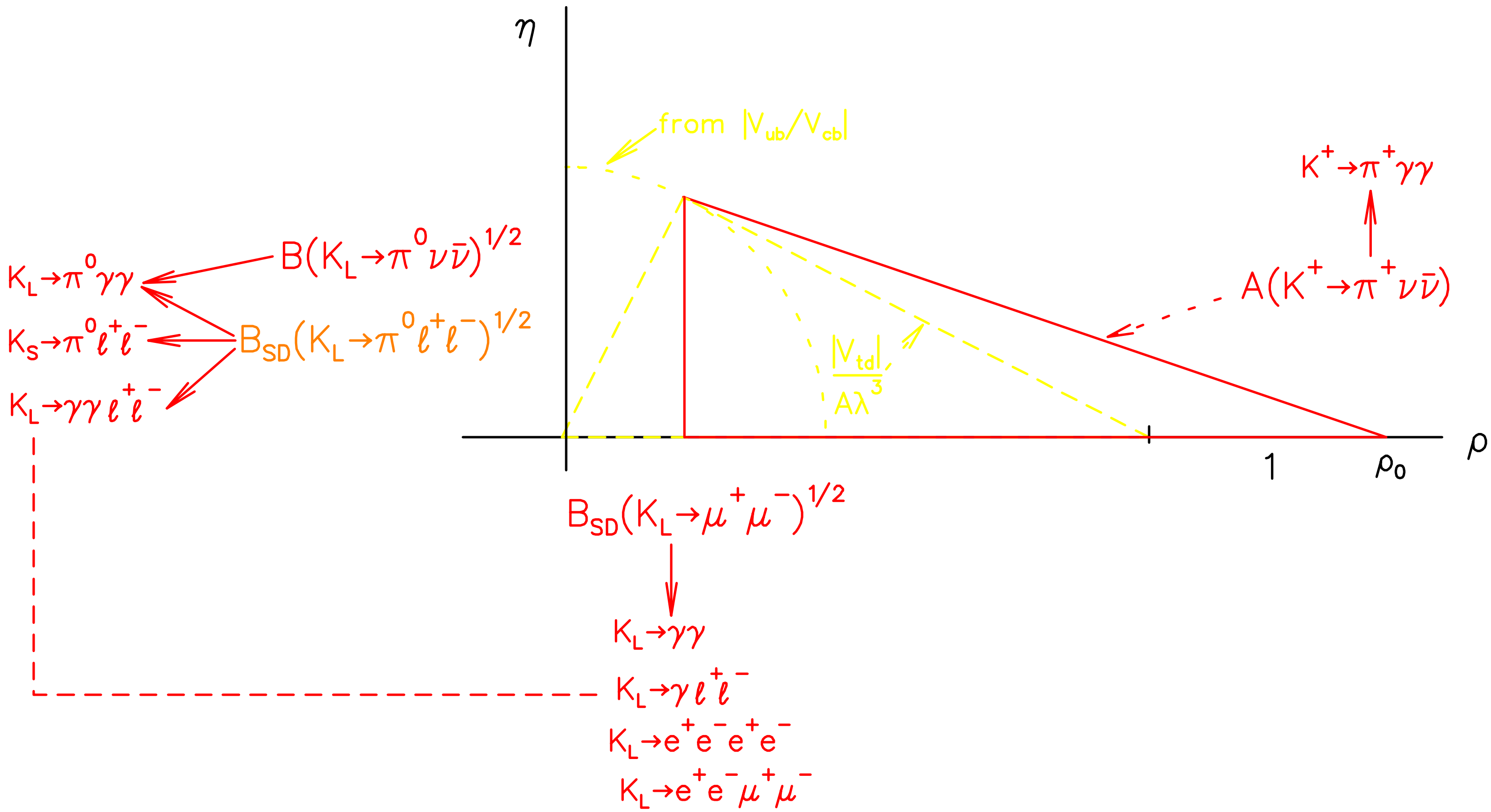


# $\underline{K_L \to \mu^+\mu^-}$

The **short distance** part of $B\left(K_L \to \mu^+\mu^-\right)$ given by:

$$B^{SD}_{\mu\mu} = \frac{\tau_{K_L}\alpha^2 B_{K^+\mu\nu}\xi}{\tau_{K^+}V^2_{us}\pi^2 sin^4\theta_W}\left[Re\left(\lambda_c\right)Y_{NL} + Re\left(\lambda_t\right)Y\left(x_t\right)\right]^2 \approx \mathcal{O}\left(10^{-9}\right)$$

where $Re\left(\lambda_c\right) = \lambda\left(\frac{\lambda^2}{2} - 1\right)$ ; $\lambda \equiv sin\theta_{Cabibbo}$; kinematic factor $\xi \approx 1$

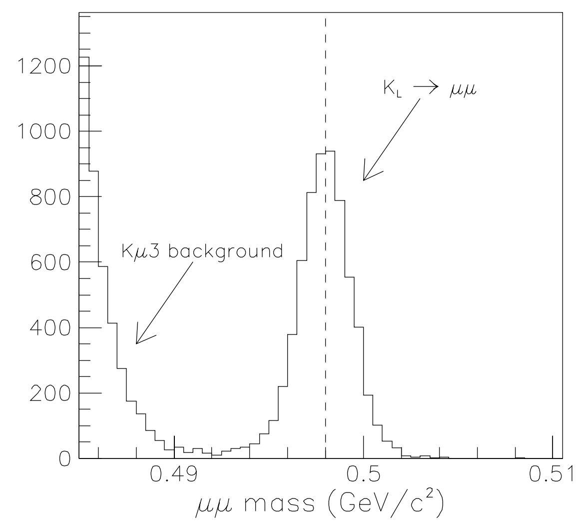
To a good approximation $Y\left(x_t\right) = 1.02\left(m_t/170\right)^{1.56}$, $Y_{NL} \approx 3 \times 10^{-4}$

$$= 1.75 \cdot 10^{-9} A^4 Y^2\left(x_t\right)\left(\bar{\rho}_0 - \bar{\rho}\right)^2 \quad = \quad (0.93 \pm 0.23) \cdot 10^{-9}$$

where $\bar{\rho}_0 \approx 1.2$

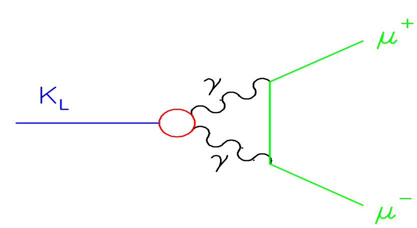
So could potentially measure $\bar{\rho}$ or be sensitive to BSM physics

Moreover there's a
Very good measurement
by AGS-871 (6000 evts!)




**But** there are a number of roadblocks to be overcome

First $B\left(K_L \to \mu^+\mu^-\right)$ is dominated
by an absorptive contribution from
intermediate $K_L \to \gamma\gamma$:




Much larger than the dispersive part which contains $B^{SD}_{\mu\mu}$!

If precise measurements are made, this can be subtracted.

# $K_L \to \mu^+\mu^-$ - 2

Actual quantity measured is

$$\frac{B(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = (3.48 \pm 0.05)\cdot 10^{-6} \qquad \text{(PDG average)}$$

So best to compare to:

$$\frac{B^{abs}_{\gamma\gamma}(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = \underbrace{\overset{\text{calculated}}{\frac{B^{abs}_{\gamma\gamma}(K_L\to\mu\mu)}{B(K_L\to\gamma\gamma)}}}_{1.2\cdot 10^{-5}}\;\underbrace{\overset{\substack{\textit{last measured}\\ \textit{by NA31 in 1987}}}{\frac{B(K_L\to\gamma\gamma)}{B\left(K_L\to\pi^0\pi^0\right)}}}_{0.632\pm 0.009}\;\overbrace{\underbrace{\overset{\substack{\textit{from several exps.}\\ \textit{last in 1976!}}}{\frac{B\left(K_S\to\pi^0\pi^0\right)}{B(K_S\to\pi^+\pi^-)}}}_{(2.185\pm 0.027)^{-1}}\;\underbrace{\left(1-6Re\frac{\epsilon'}{\epsilon}\right)}_{1-6\,(17.2\pm 1.8)\cdot 10^{-4}}}^{\frac{B\left(K_L\to\pi^0\pi 0\right)}{B(K_L\to\pi^+\pi^-)}}$$

$$= (3.435 \pm 0.065)\cdot 10^{-6}$$

$$\frac{B^{disp}(K_L\to\mu\mu)}{B(K_L\to\pi^+\pi^-)} = (0.045 \pm 0.082)\cdot 10^{-6}$$

Then multiply by $B\left(K_L \to \pi^+\pi^-\right) = (2.056 \pm 0.033)\cdot 10^{-3}$ (PDG fit)

To get $B^{disp}(K_L \to \mu\mu) = (0.093 \pm 0.169)\cdot 10^{-9}$
*i.e.*

$$B^{disp}(K_L \to \mu\mu) < 0.31 \cdot 10^{-9} \text{ at } 90\% \text{ c.l.}$$

Disagrees with $B^{SD}_{\mu\mu} = (0.93 \pm 0.23)\cdot 10^{-9}$ by $> 3\sigma$!

Why haven't we been hearing about this?

# $\underline{K_L \to \mu^+\mu^- \text{ - } 3}$

Problem is long distance contribution to $B^{disp}(K_L \to \mu\mu)$
This can interfere with the short distance amplitude
To untangle, must know $A(K_L \to \gamma\gamma)$ with $\gamma$s off mass-shell
- size, calculability controversial:

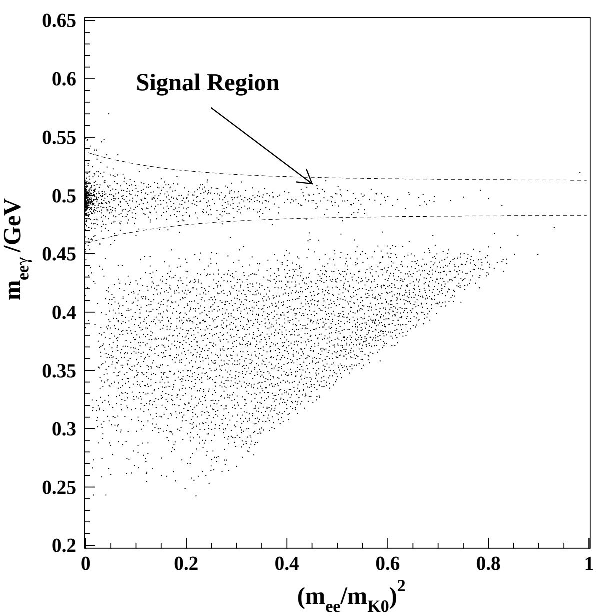
| Pro | Con |
|---|---|
| Gomez-Dumm *et al.*, PRL **80** (1998) 4633 | Valencia NP B **517** (1998) 339 |
| D'Ambrosio *et al.*, PL B **423** (1998) 385 | Knecht *et al.*, PRL **83** (1999) 5230 |

Can one **measure** this?

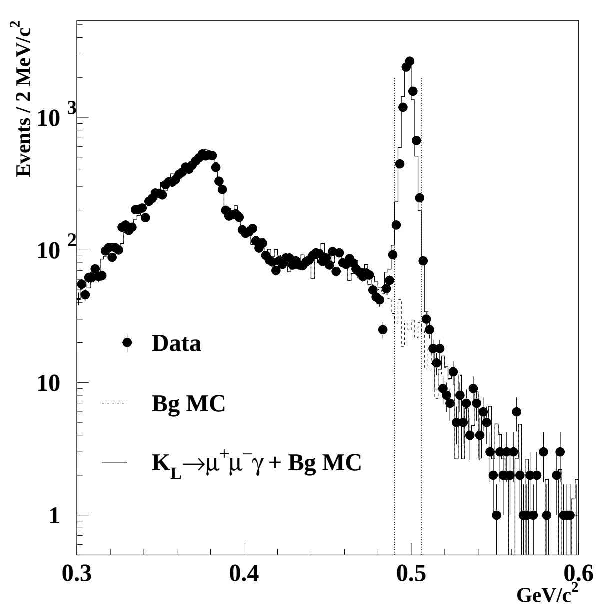
There are recent results on:

| | |
|---|---|
| $K_L \to ee\gamma$ | NA48 |
| $K_L \to \mu\mu\gamma$ | KTeV |
| $K_L \to eeee$ | KTeV, NA48 |
| $K_L \to ee\mu\mu$ | KTeV, NA48 |

People have used fits to some of these to put a limit on $\rho$,
- how legitimate this is is still unclear




Scatter plot of $e^+e^-\gamma$ mass versus $m^2_{ee}/m^2_{K^0}$. The dashed lines define the signal region. From NA48.



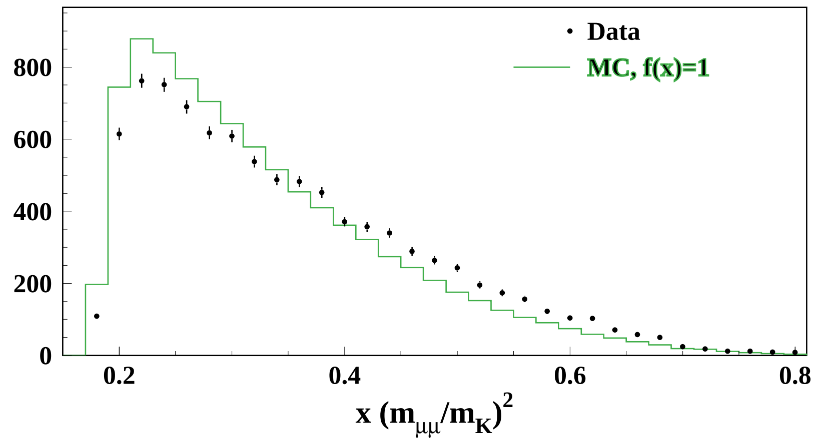

$\mu\mu\gamma$ mass from KTeV

# Virtual photon form factors

Virtual photon form factors are needed to calculate the long-distance dispersive contribution to $K_L \to \mu^+\mu^-$.

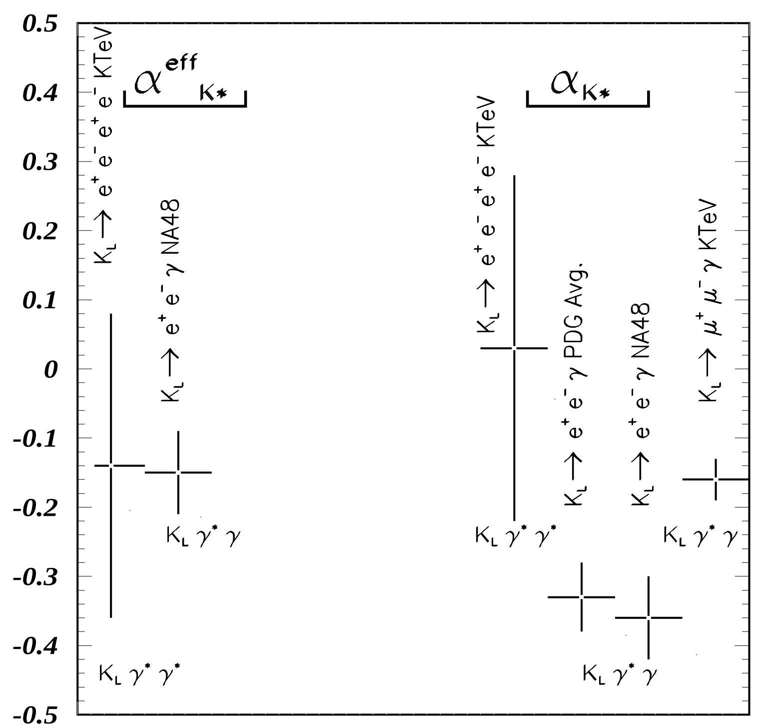
That these processes not pointlike, now clear:

Data at right from KTeV $m_{\mu\mu}$ dist. in $K_L \to \mu^+\mu^-\gamma$




There are a couple of form factor parameterizations on the market; the traditional one is Bergström, Massó, & Singer (BSM), with parameter $\alpha_{K^*}$

Figure at right shows $\alpha_{K^*}$ from recent experiments. (From E. Halkiadakis thesis)




Agreement not inspiring but proper radiative corrections may help.

+ some issues not apparent in figure

Finally, different parameterizations give different results, *e.g.* from KTeV $K_L \to \mu\mu\gamma$ :

$$|ReA_{LD}^{BMS}| < 3.6 \times 10^{-5} \text{ but } |ReA_{LD}^{DIP}| < 2.07 \times 10^{-5}$$

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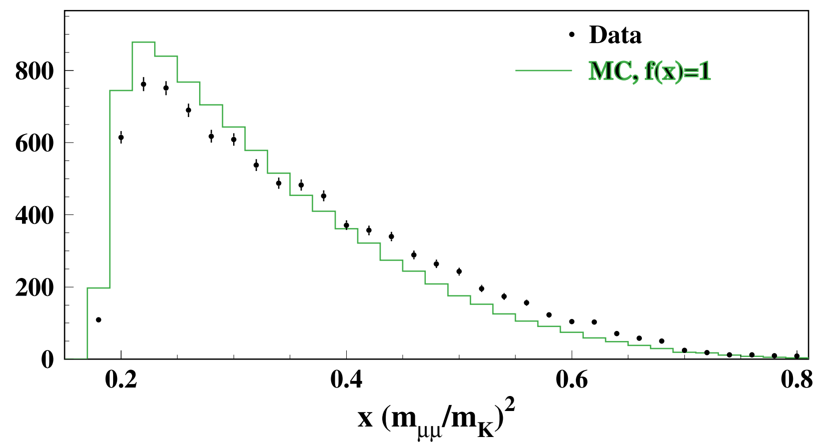


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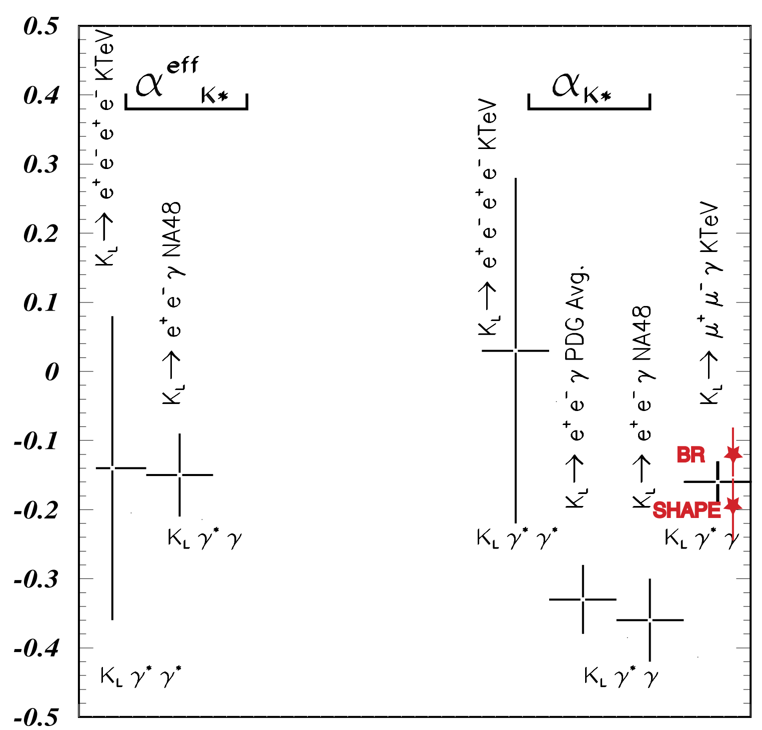
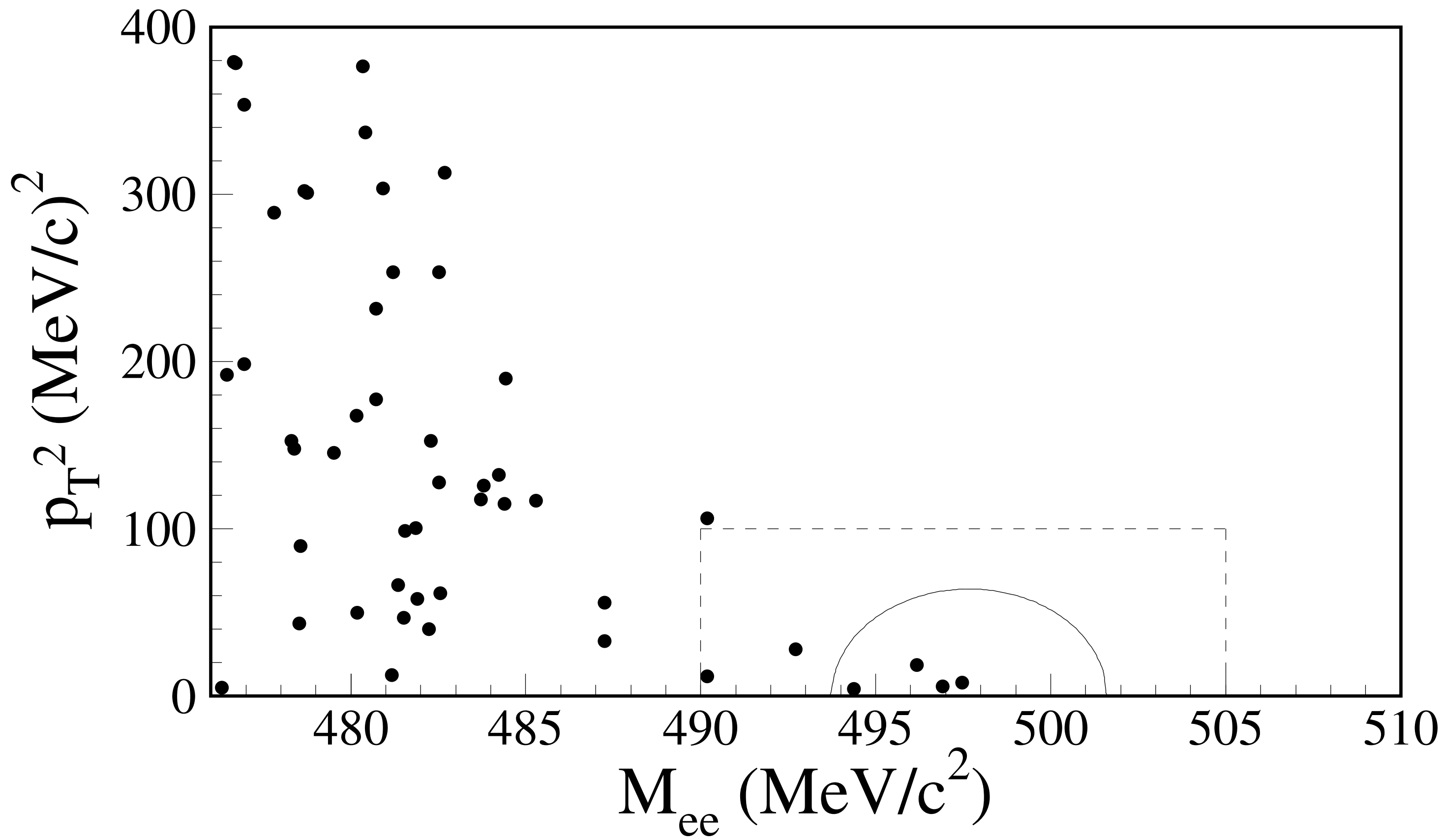



Finally, different parameterizations give different results, *e.g.* from KTeV $K_L \to \mu\mu\gamma$ :

$$|ReA_{LD}^{BMS}| < 3.6 \times 10^{-5} \text{ but } |ReA_{LD}^{DIP}| < 2.07 \times 10^{-5}$$

# E871 Measurement of $K_L \to e^+e^-$




AGS-871 observed four $K_L \to e^+e^-$ candidates
with expected background $0.17 \pm 0.10$ events

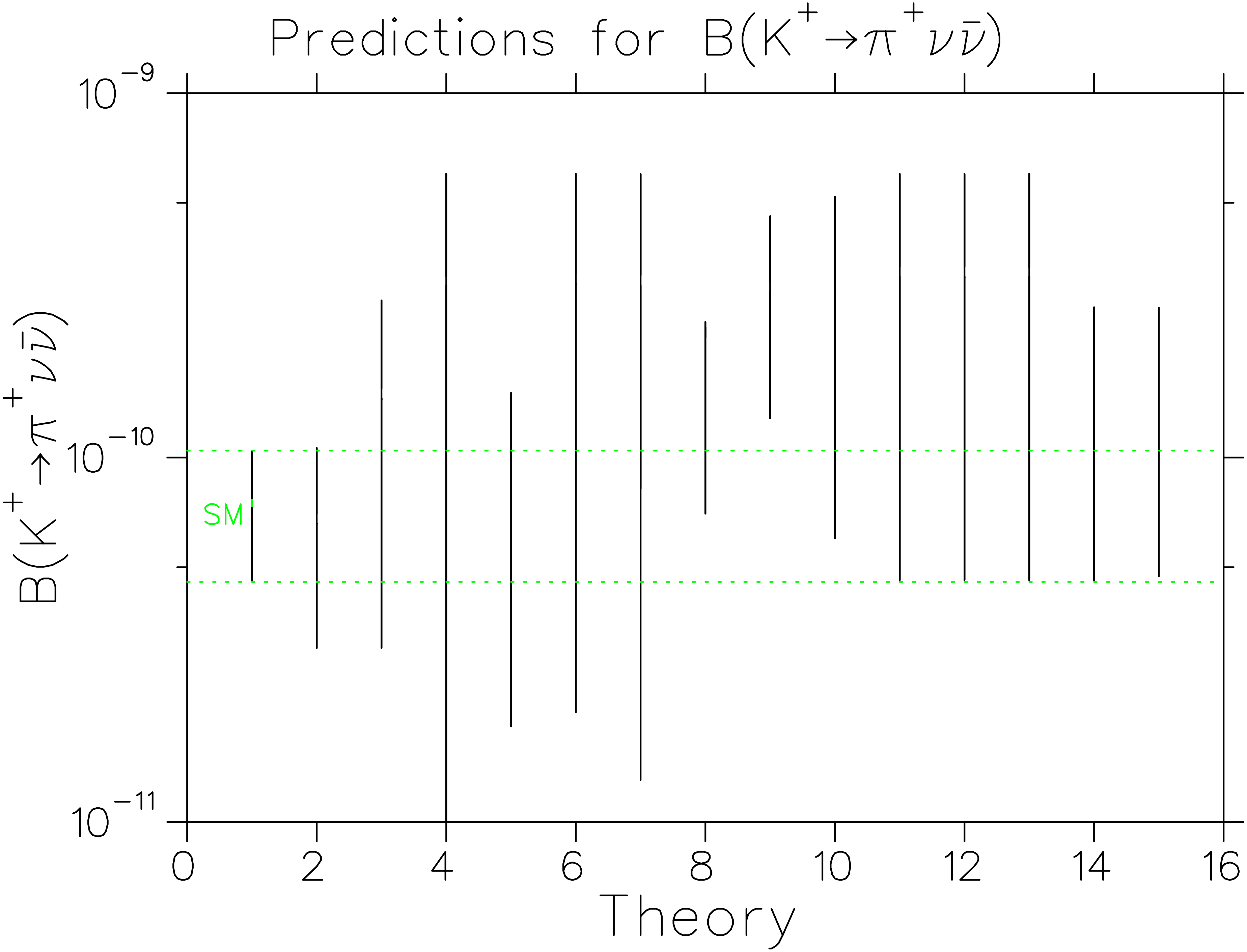
They obtain $B(K_L \to e^+e^-) = (8.7^{+5.7}_{-4.1}) \times 10^{-12}$

Lowest BR ever measured

Unfortunately can't be used to get short distance information.

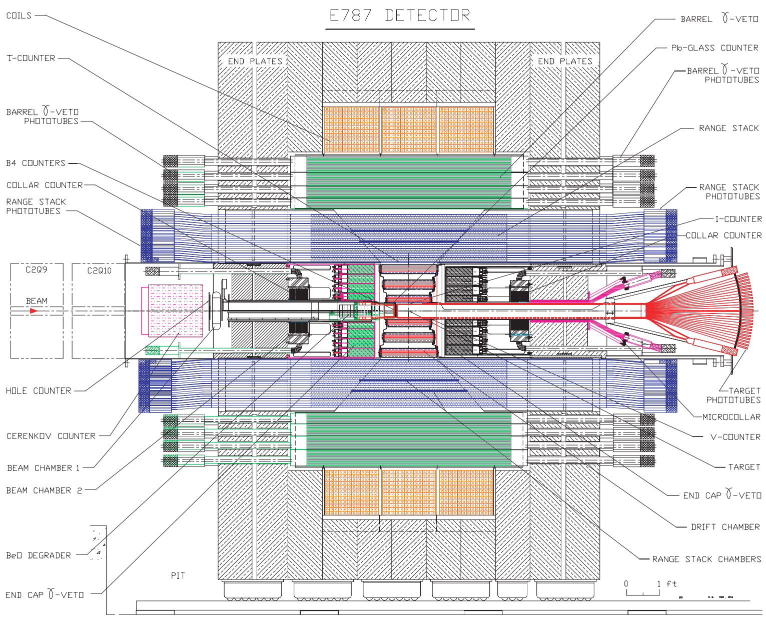
- ironically, long-distance real part reliably calculable.
- just too big!

Existence proof of observation of a $K$ decay at $< 10^{-11}$.

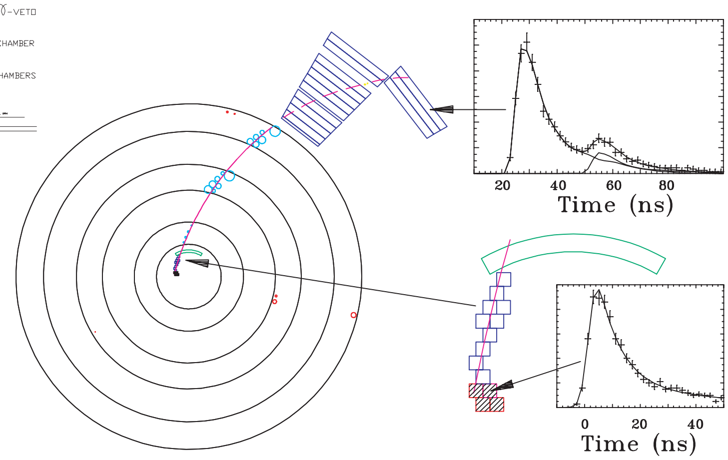


Predictions for $B(K^+\to\pi^+\nu\bar{\nu})$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$B(K^+\to\pi^+\nu\bar{\nu})$
SM
0
2
4
6
8
10
12
14
16
Theory

# AGS-E787




First event in 1995 data set:




1995-7 data set still had only 1 event, with bckgnd $< 0.1$ evts.

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = (1.5^{+3.4}_{-1.2}) \times 10^{-10} \ (\sim \text{twice SM}).$$

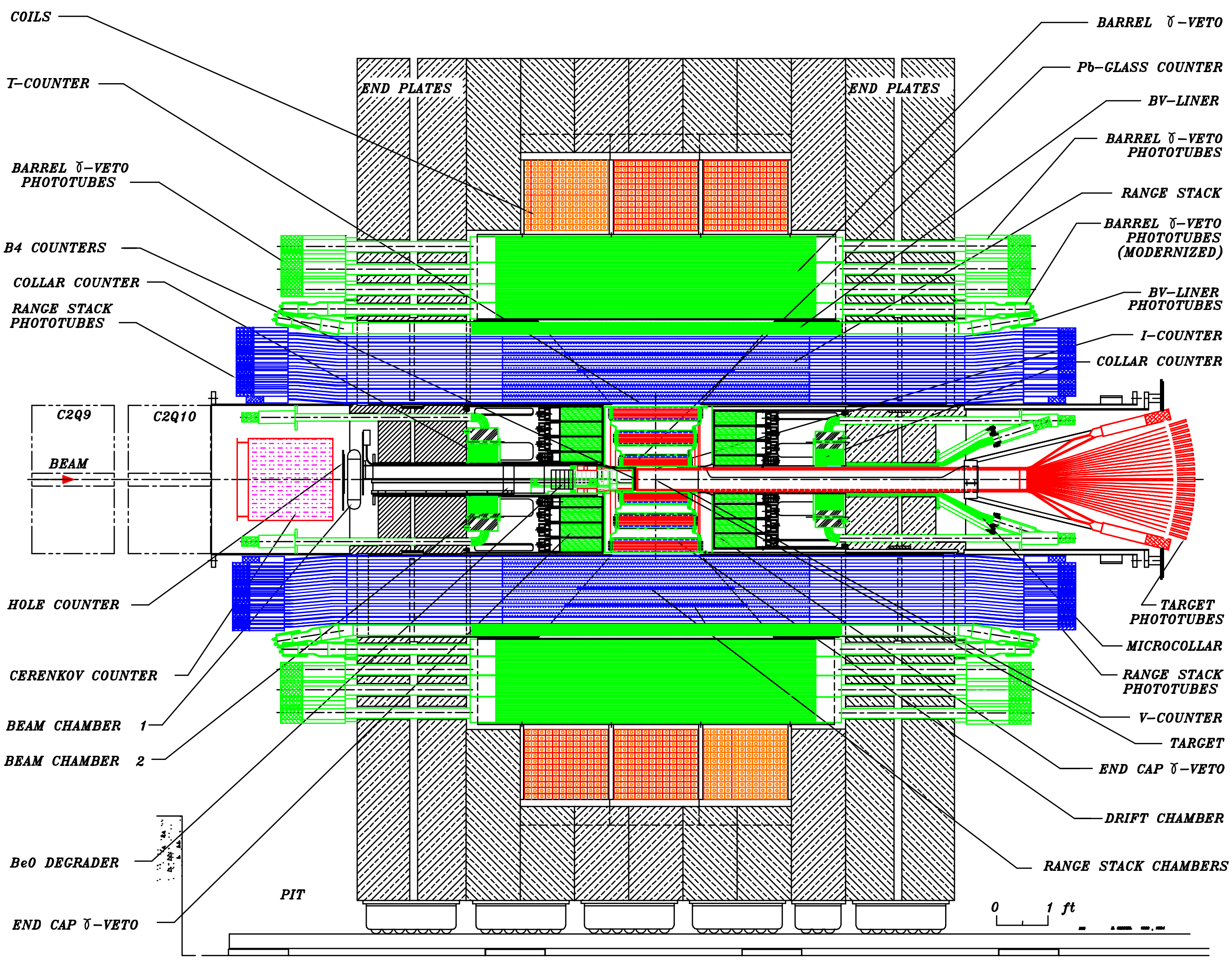
1998 data set $\approx$ to all previous E787 data
- background very similar to that of 1995-7:

| Background type | 1998 (prelim.) | 1995-7 |
|---|---|---|
| $K^+ \to \mu^+ \nu$ | $0.034 \pm 0.044$ | $0.0282 \pm 0.0097$ |
| $K^+ \to \pi^+ \pi^0$ | $0.035 \pm 0.035$ | $0.0212 \pm 0.0049$ |
| beam (1) | $0.004 \pm 0.001$ | $0.0042 \pm 0.0032$ |
| beam (2) | $0.000 \pm 0.000$ | $0.0027 \pm 0.0023$ |
| charge exchange | $0.012 \pm 0.002$ | $0.0096 \pm 0.0068$ |
| total | $0.085 \pm 0.056$ | $0.0786 \pm 0.0198$ |

Stay tuned!

# E949 Measurement of $B(K^+ \to \pi^+ \nu \bar{\nu})$

Albera, UBC, BNL, FNAL, Fukui, IHEP, INR, KEK, JAERI, Kyoto, NDAJ, New Mexico, Osaka, RCNP, TRIUMF




Upgrade of BNL AGS 787

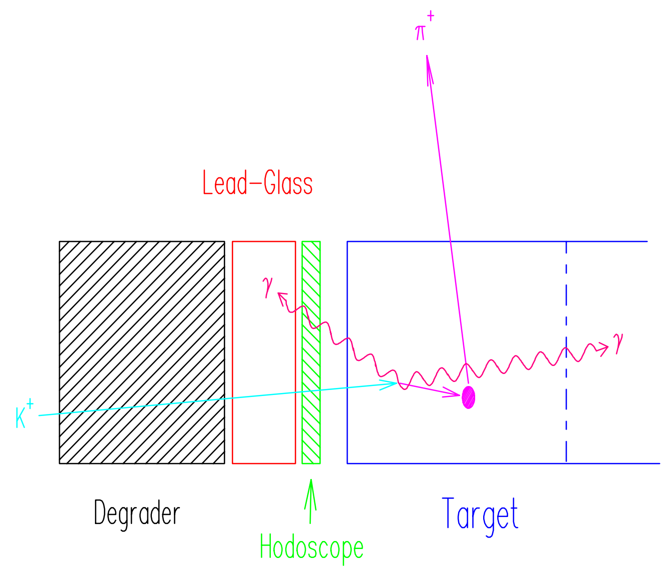
Sensitivity improvement with respect to E787 (1995):

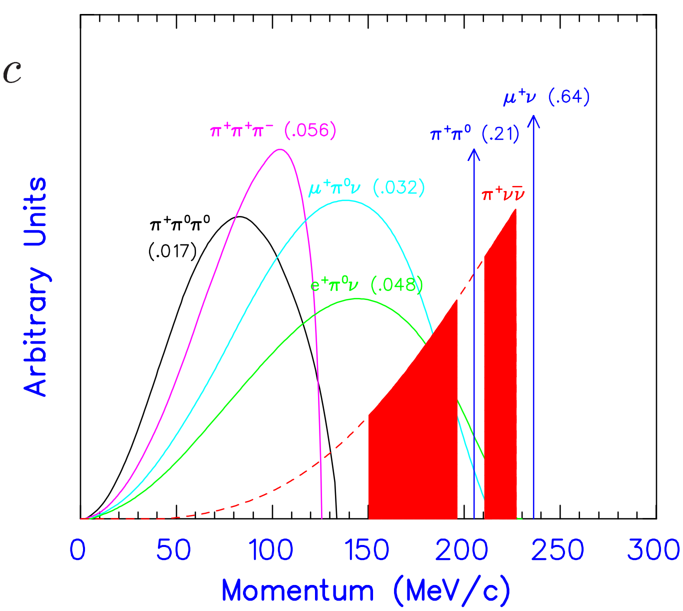
- Increased spill length ($\times 1.56$)
- Lower momentum ($\times 1.38$)
- Increased efficiency (trigger, DAQ, analysis) ($\times 3.2$)
- Acc. below $K\pi 2$ + higher rate analysis reopt. ($\times 2$)
- Total gain - $\times 14$ per hour of data taking

Expect to reach $\sim 10^{-11}$/evt by 2004

# $K^+ \to \pi^+ \nu\bar{\nu}$ "below the $K\pi2$"

$\approx$ all $K^+ \to \pi^+ \nu\bar{\nu}$ sensitivity so far
In kinematic region $P_{\pi^+} > 205\text{MeV}/c$
Softer $p_{\pi^+}$ region suffers from
$K^+ \to \pi^+\pi^0$ downshift +
correlated $\gamma$ inefficiency:



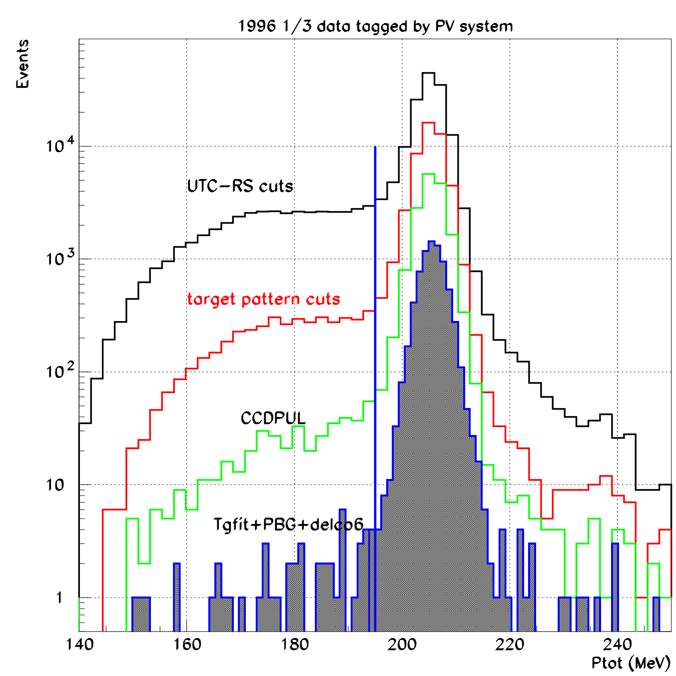




Correlation between photon veto
and nuclear interactions

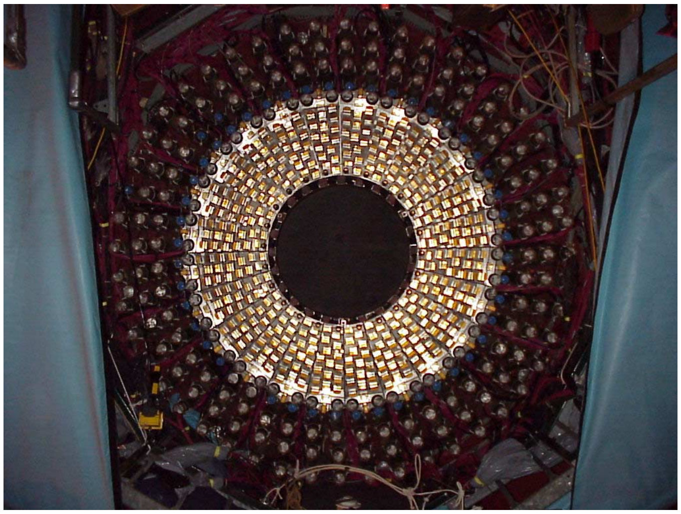
Major effort to clean up region
Now bearing fruit.

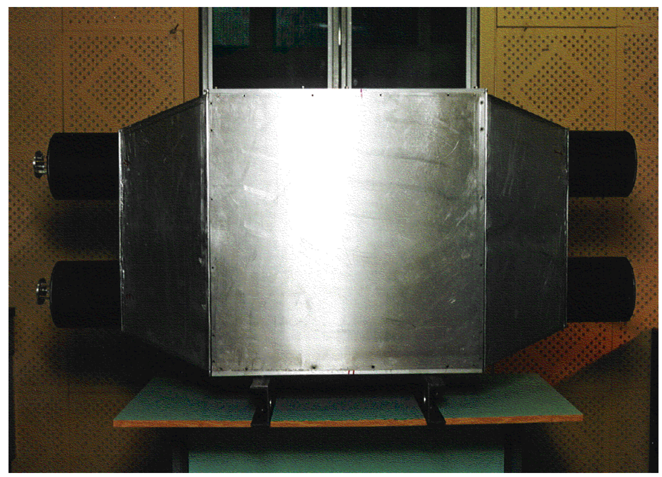
One year of E787 data
Gives s.e.s. $\sim 10^{-9}$
w/background of 0.7 events

Expect E949 upgrade to
improve by factor 10



# Status of E949





Almost all hardware upgrades completed & installed

Commissioning run in progress

New systems work well - being calibrated

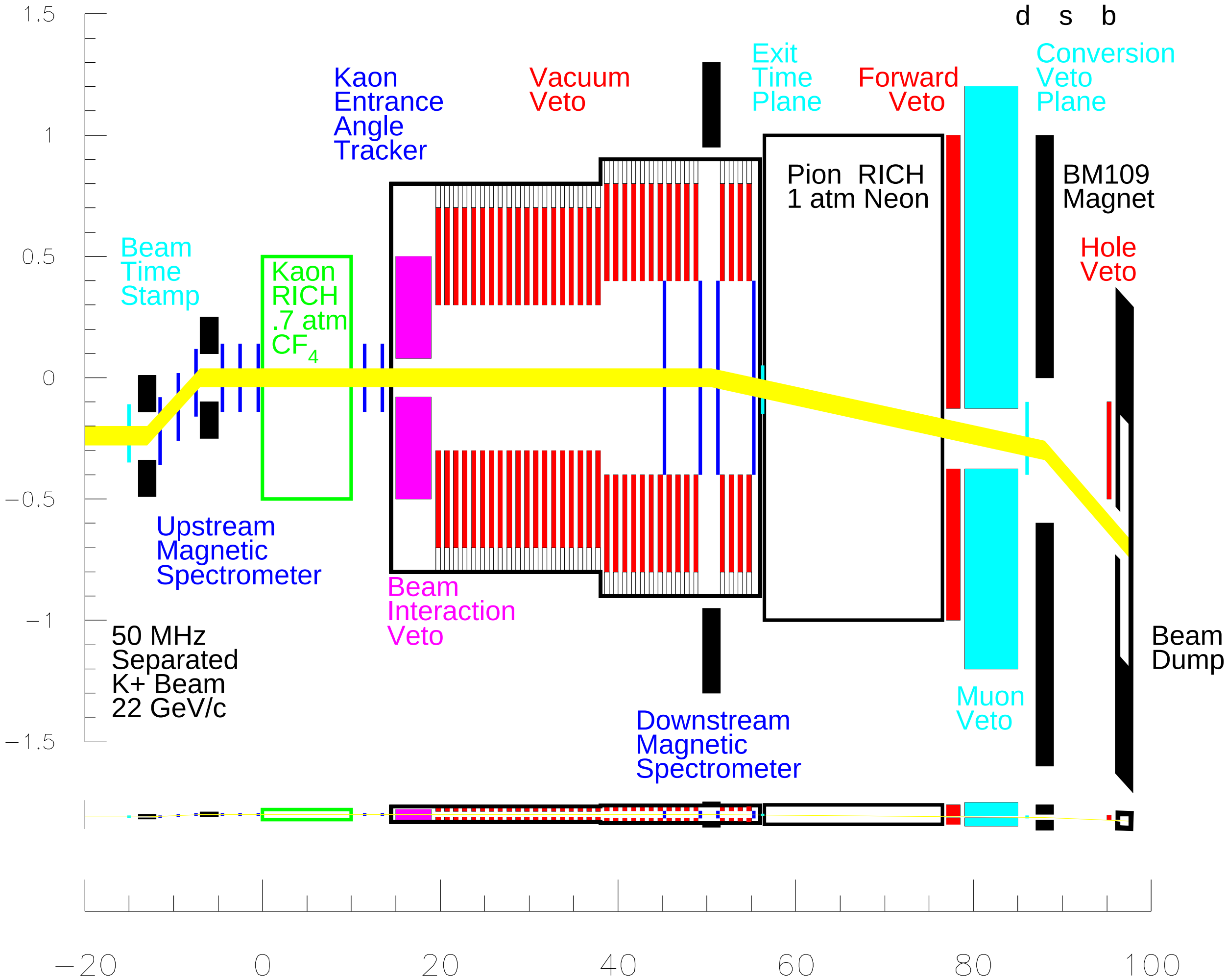
Technique for heavy ions/protons switch tested

RHIC running getting smoother

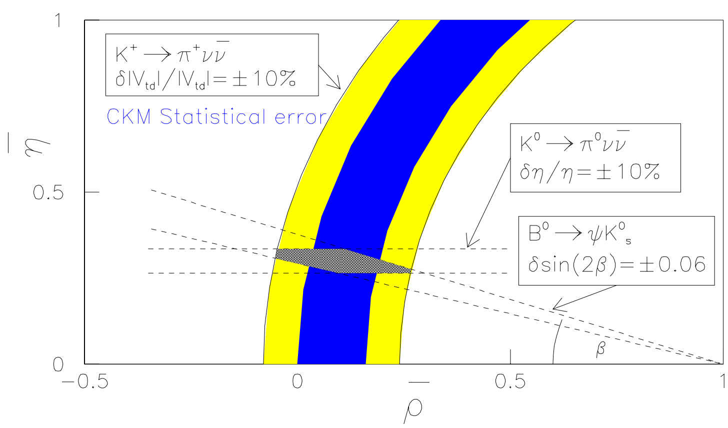
# CKM Experiment to Measure $K^+ \to \pi^+ \nu \bar{\nu}$

New, in-flight technique:

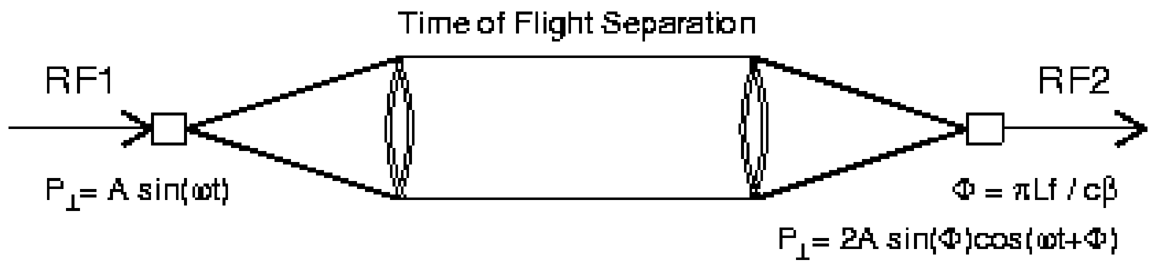
**CKM Apparatus**



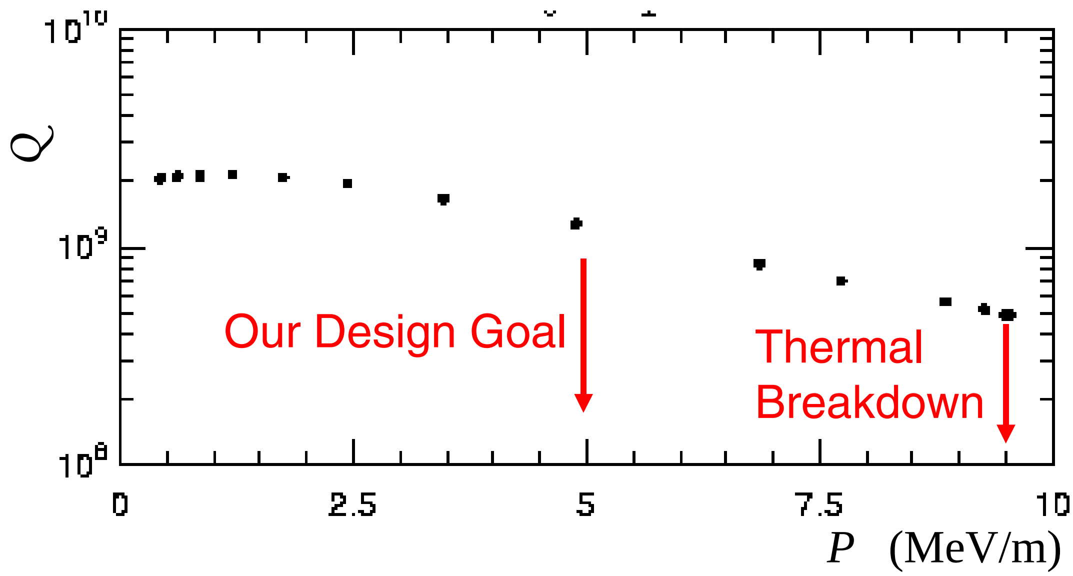

Reach for $\sim 100$ events:



# RF separated $K^+$ beam




*A recent 1-cell test result:*

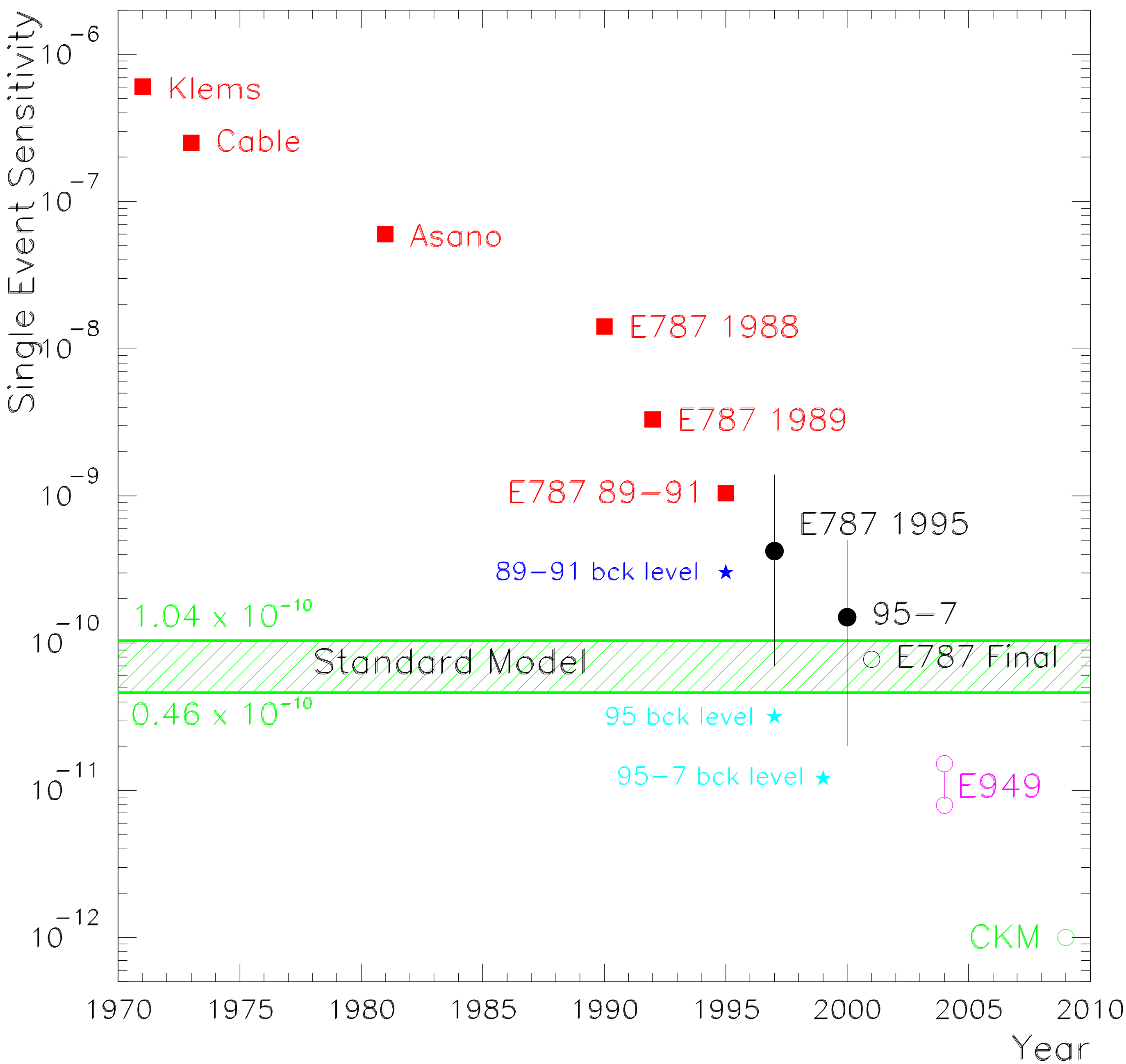



Expressed as $B_{MAX}$ on inner Nb surface:

| | |
|---|---|
| This result: | 104mT |
| Our design @ 5MeV/m: | 77mT |
| TESLA @25 MeV/m: | 110mT |
| TESLA @35 MeV/m: | 160mT |

# Progress in $K^+ \to \pi^+ \nu \bar{\nu}$

- E787 observed 1 event in 1995 run
- Analysis of 1995-7 data shows background rejection adequate for measurement at the S.M. level.
- Data collected in 1998 equal in sensitivity to previous total.
- Full E787 data sample (1995–98) will reach S.M. level.
- E949 should reach $\mathcal{O}(10^{-11}/\text{evt})$ with $\sim 10$ S.M. events
- CKM proposes to reach $\mathcal{O}(10^{-12}/\text{evt})$ by $\sim 2010$



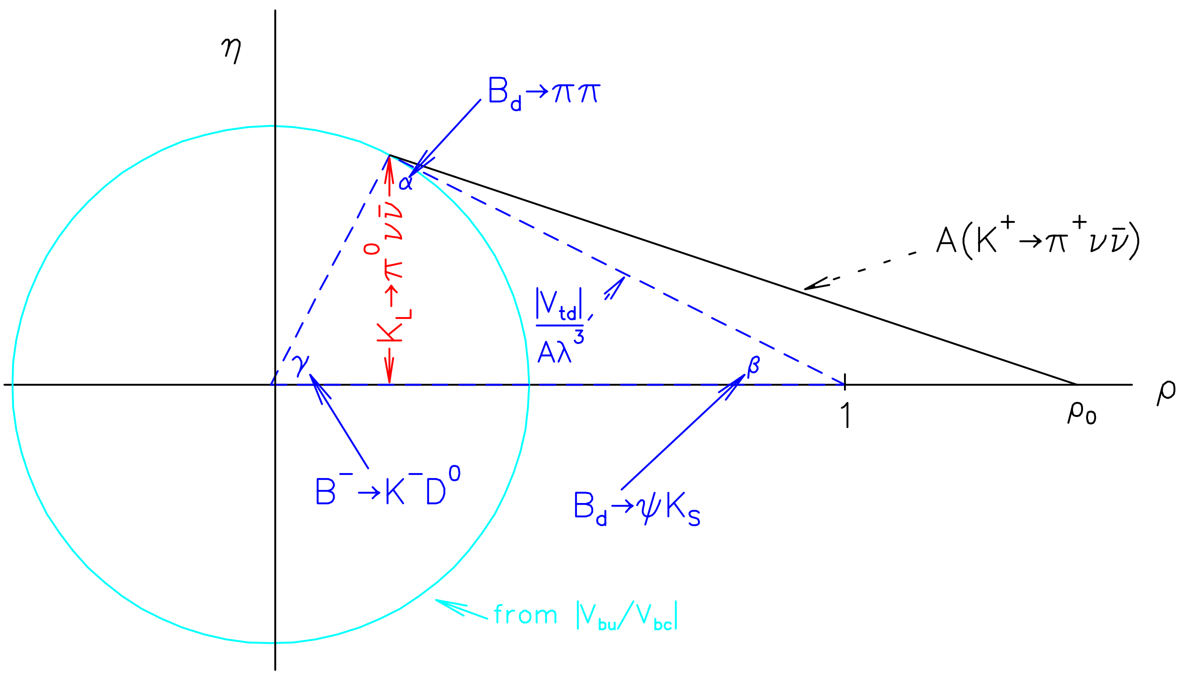
# $K_L \to \pi^0 \nu \bar{\nu}$ in the Standard Model

Pure direct CP-violating (state-mixing very small)

Calculation in terms of fundamental parameters good to $\lesssim 2\%$

In terms of usual unitarity triangle parameterization:

$$B(K_L \to \pi^0 \nu \bar{\nu}) = 4 \cdot 10^{-10} A^4 \eta^2$$




Gives height of UT without triangulation

- with $K^+ \to \pi^+ \nu \bar{\nu}$ can determine $\rho$ as well

Also note that

$$B(K_L \to \pi^0 \nu \bar{\nu}) = 1.56 \cdot 10^{-4} [Im(V_{ts}^* V_{td})]^2 \equiv 1.56 \cdot 10^{-4} [Im \lambda_t]^2$$

$Im \lambda_t$ presently triangulated to $\sim 20\%$,

- A dedicated experiment could directly measure it to 10%

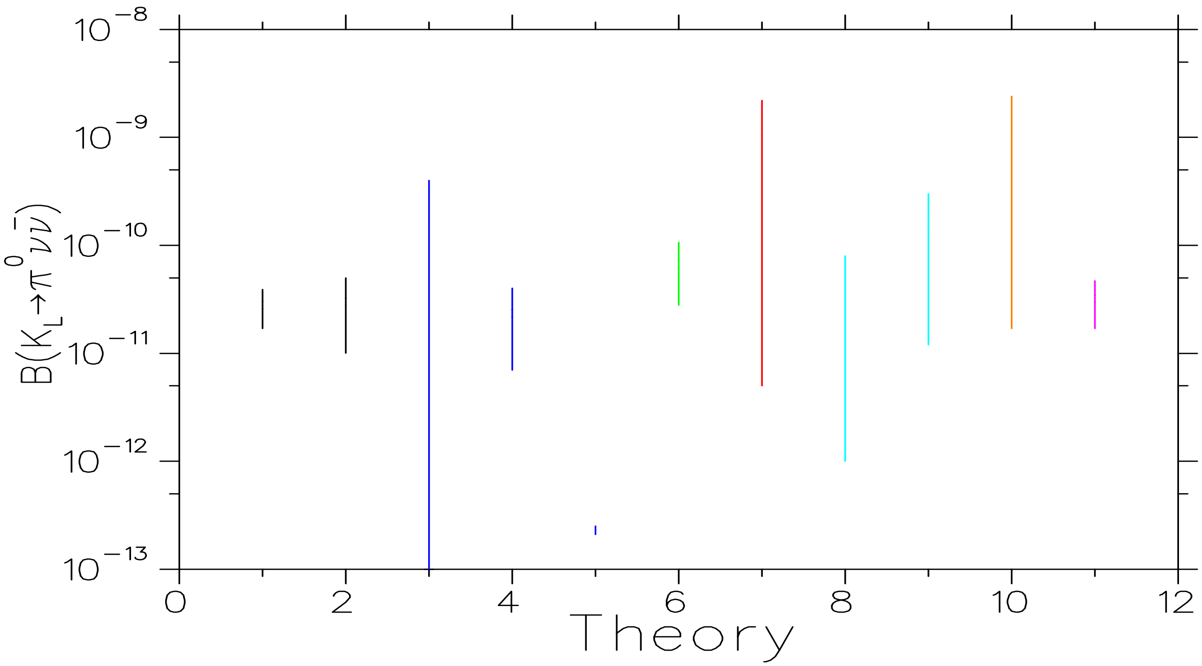
There are only a few solid measurements on the UP

- none is better!

# $K_L \to \pi^0 \nu\bar{\nu}$ Beyond the Standard Model

| | Who | What | $10^{11} B(K_L \to \pi^0 \nu\bar{\nu})$ |
|---|---|---|---|
| 1 | Buchalla | Standard Model CKM fit | $2.8 \pm 1.1$ |
| 2 | Plaszczynski/Schune | Conservative SM fit | $1 - 5$ |
| 3 | Buras, *et al.* | Generic SUSY w/min. part. content | $0 - 40$ |
| 4 | Buras, *et al.* | MSSM w/o new flavor or CP viol. | $(0.41 - 1.03)\times$ SM |
| 5 | Brhlik, *et al.* | all CP-viol. due to SUSY | $\sim .023$ |
| 6 | Chanowitz | $SU(2)_L \times SU(2)_R$ Higgs | $2.8 - 10.6$ |
| 7 | Hattori, *et al.* | 4th generation | $0.5 - 260$ |
| 8 | Xiao, *et al.* | top-color assisted technicolor | $0.1 - 8$ |
| 9 | Xiao, *et al.* | multiscale walking technicolor | $1.2 - 30$ |
| 10 | Grossman/Nir | Extra “vector-like” quarks | $1.7 - 260$ |
| 11 | Kiyo, *et al.* | seesaw L-R model† | $(1 - 1.2)\times$ SM |

† predicts spectrum will be altered.



# A Model Independent Limit on $B(K_L \to \pi^0 \nu\bar{\nu})$

$B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 4.4 \times B\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$

Proposed by Y. Grossman & Y. Nir

- Phys. Lett. **B398**, 163 (1997)

A consequence of $\Delta I = \frac{1}{2}$ rule

- trivial in SM
- true in for almost any short-distance interaction even if that interaction conserves CP

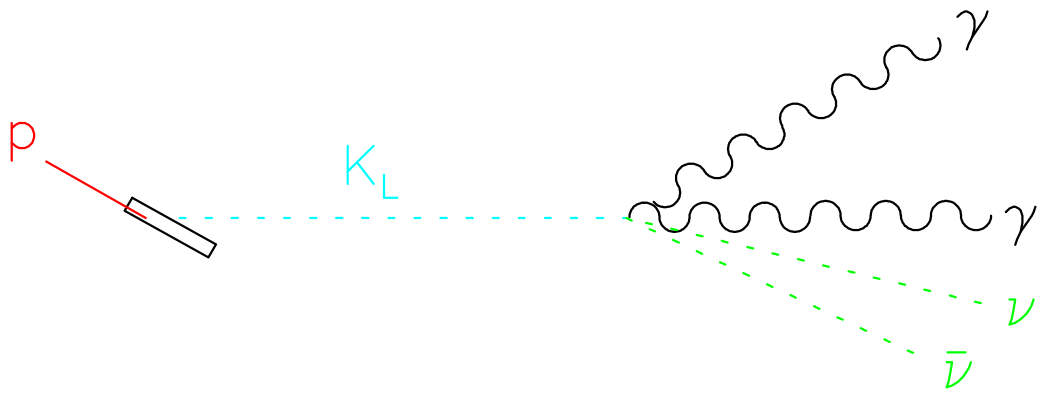
'95-7 E787 result is $B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.5^{+3.4}_{-1.2}\right) \times 10^{-10}$

This leads to $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 2.6 \times 10^{-9}$ at 90% c.l.

Far better than any other current limit

- but still 100 times larger than SM expectation

# $K_L \to \pi^0 \nu \bar{\nu}$ experimental issues




All neutral initial & final state, $\gamma$'s make $\pi^0$

Expected branching ratio $3 \times 10^{-11}$
- need high flux of $K_L$

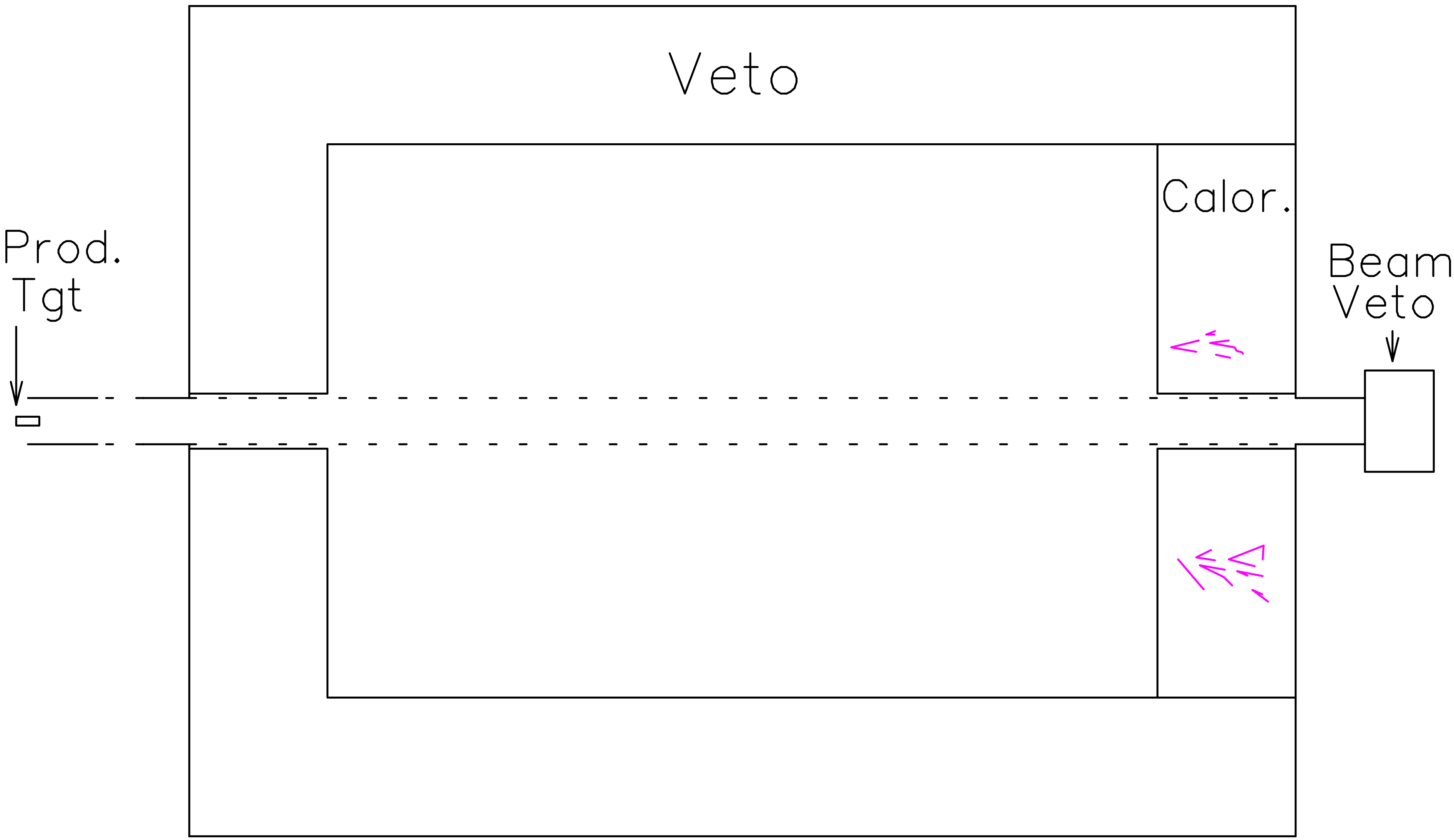
Largest background $K_L \to \pi^0 \pi^0$, BR $\sim 10^{-3}$
- need excellent vetoing, other handles if possible

Background from neutron-produced $\pi^0$'s, $\eta$'s
- requires vacuum of $10^{-7}$
- need to make sure decay vertex was in beam

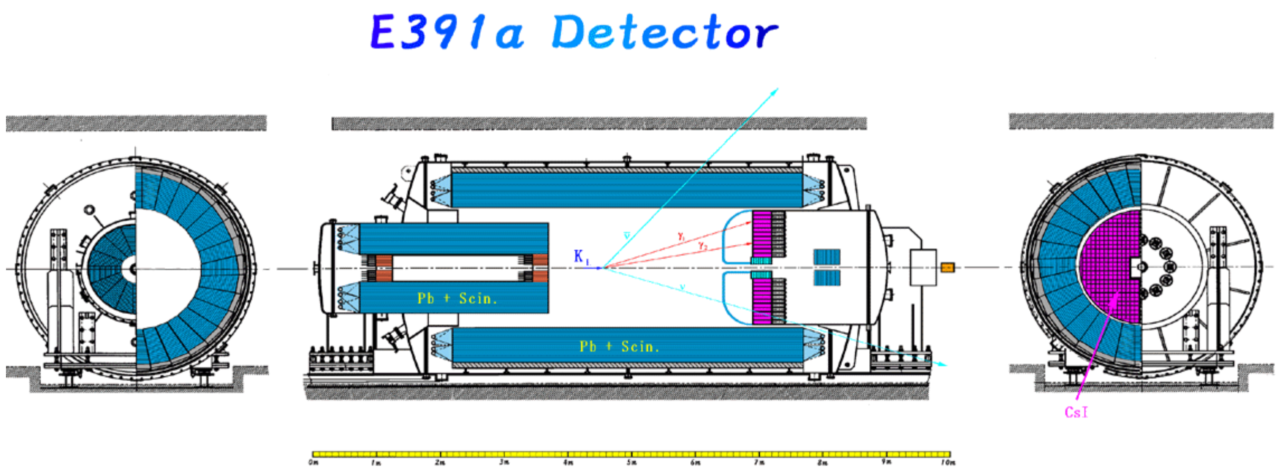
Potential backgrounds from hyperon decay $\pi^0$'s
- could use a clever way of getting rid of them

Present status: $B(K_L \to \pi^0 \nu \bar{\nu}) < 5.9 \times 10^{-7}$
- from KTeV, using Dalitz-converted $\pi^0$'s

# $K_L \to \pi^0 \nu \bar{\nu}$ Experiment



# KEK E391a search for $K_L \to \pi^0 \nu \bar{\nu}$




Carefully designed "pencil" beam, compact detector

Entire apparatus in vacuum

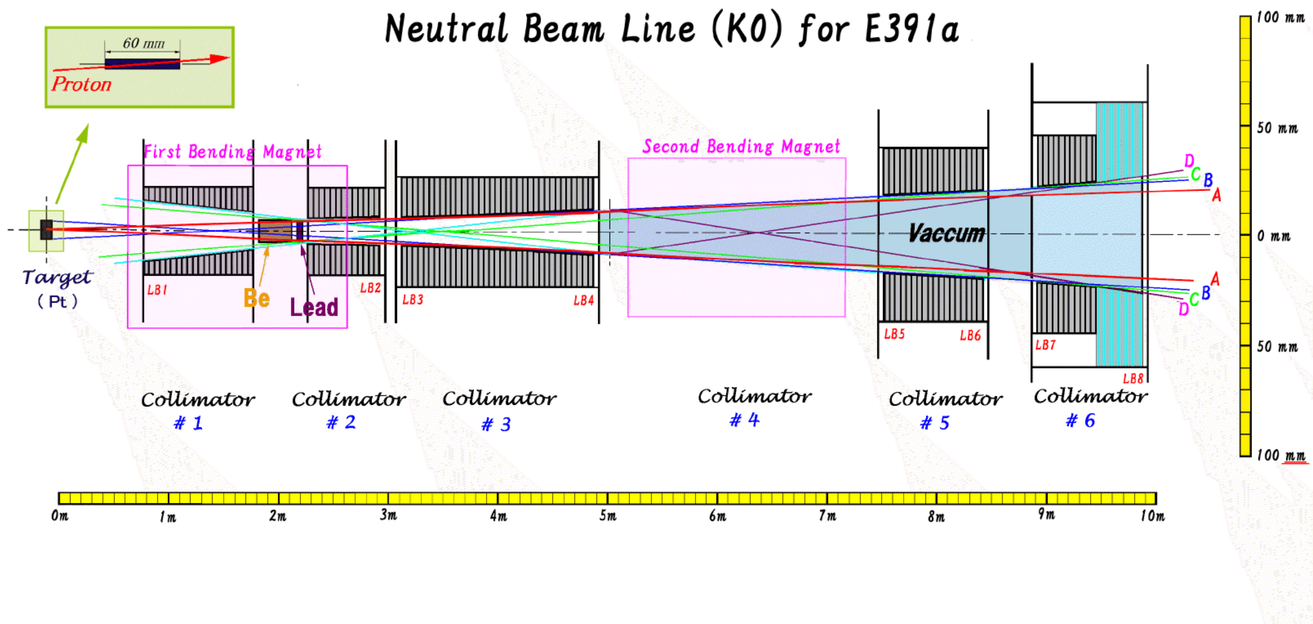
Very high performance photon veto

Expected to reach $\sim 3 \times 10^{-10}$ single event sensitivity
- *i.e.* w/i an order of magnitude of S.M. prediction

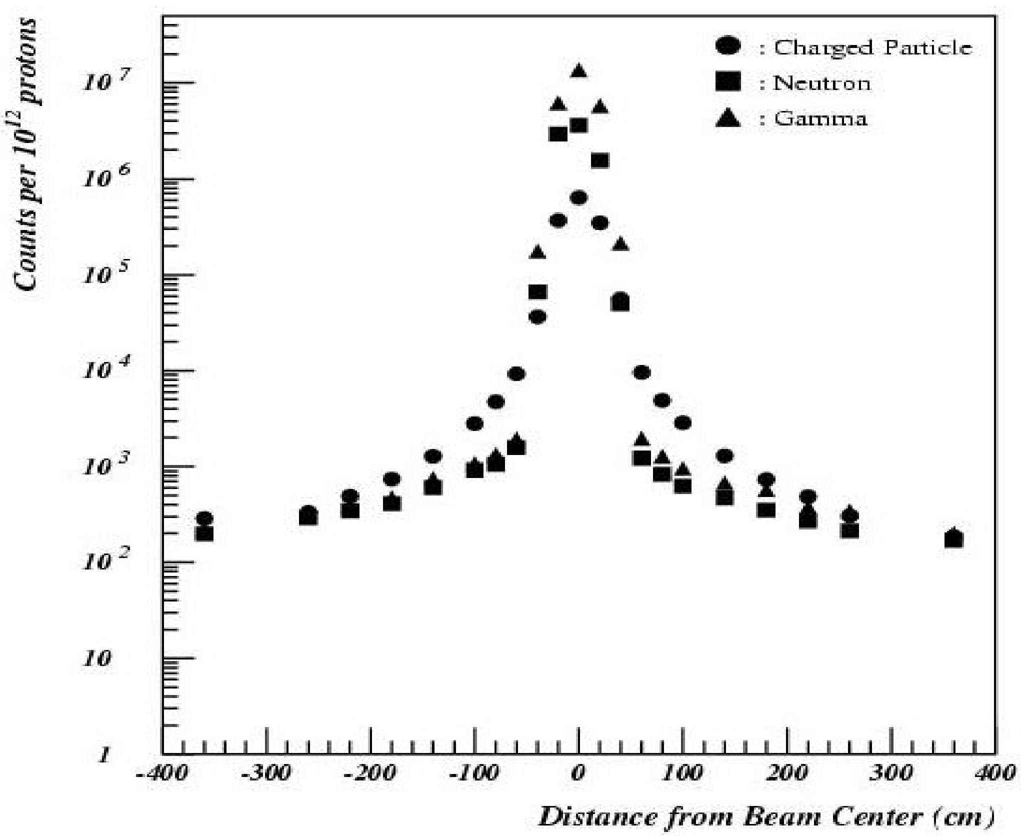
Beamline construction & tuning begun in March 2000

Run start scheduled for Fall, 2003

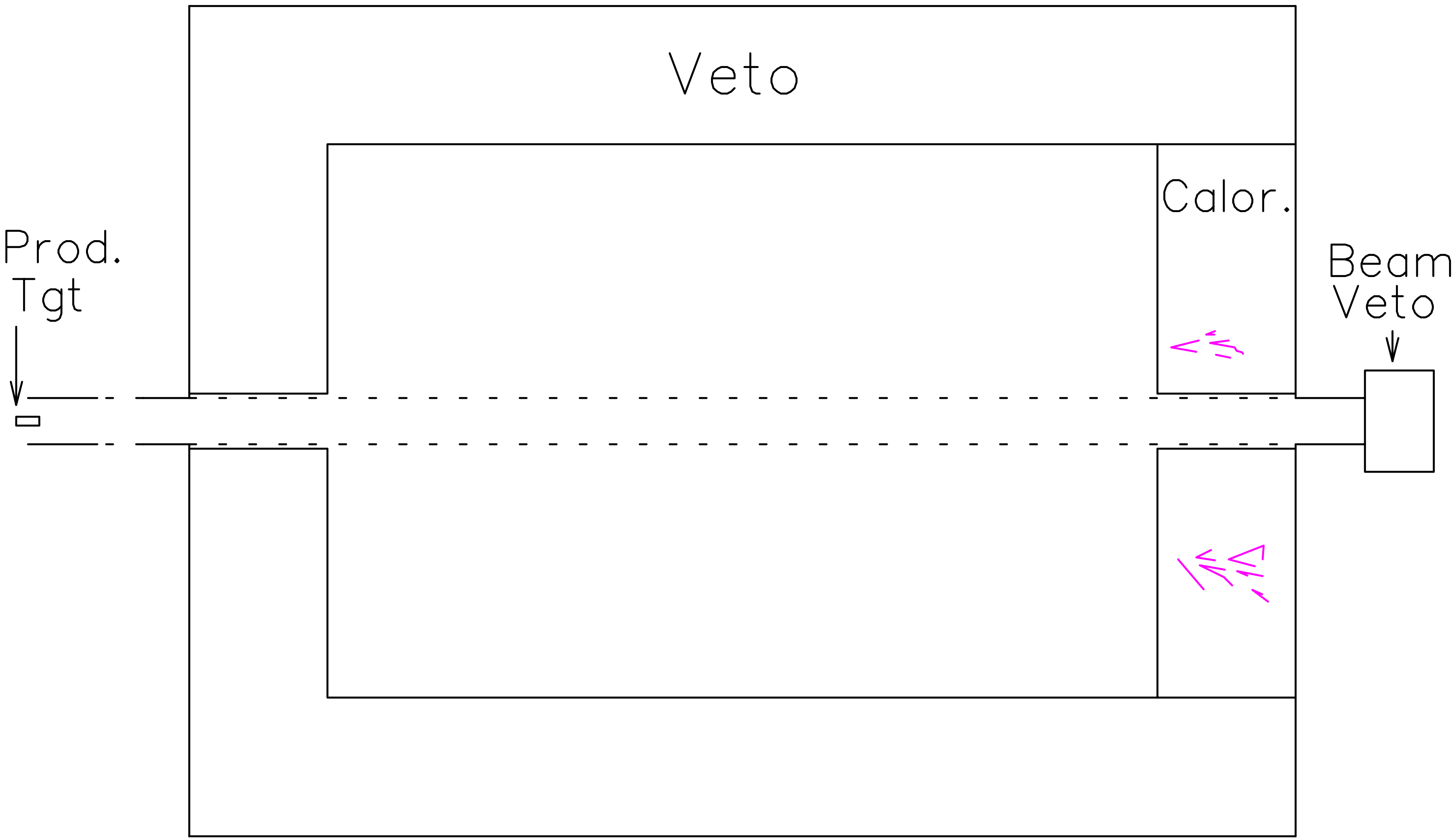
Test bed for JHF experiment



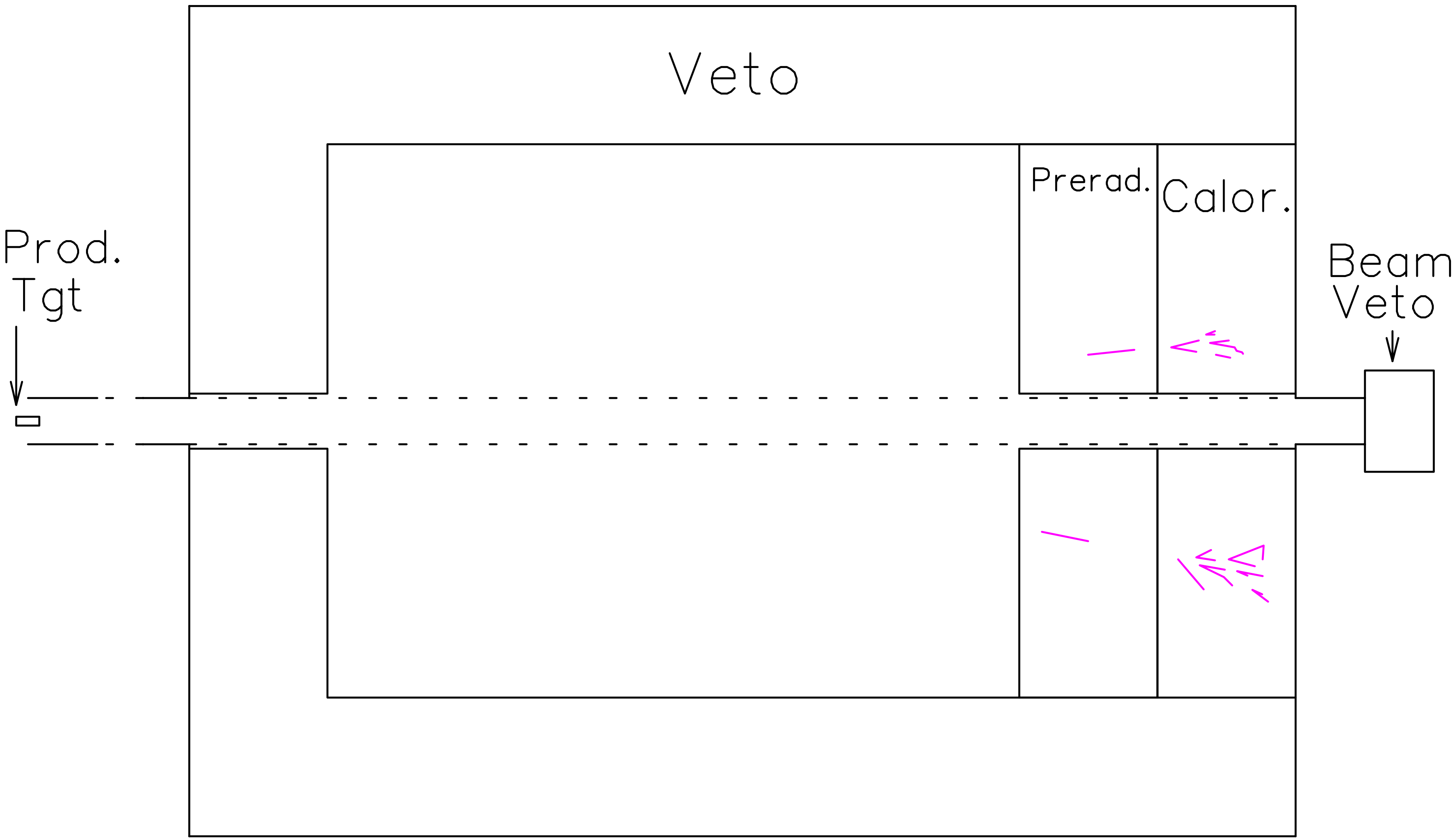

Critical to reduce the beam halo. Tests encouraging



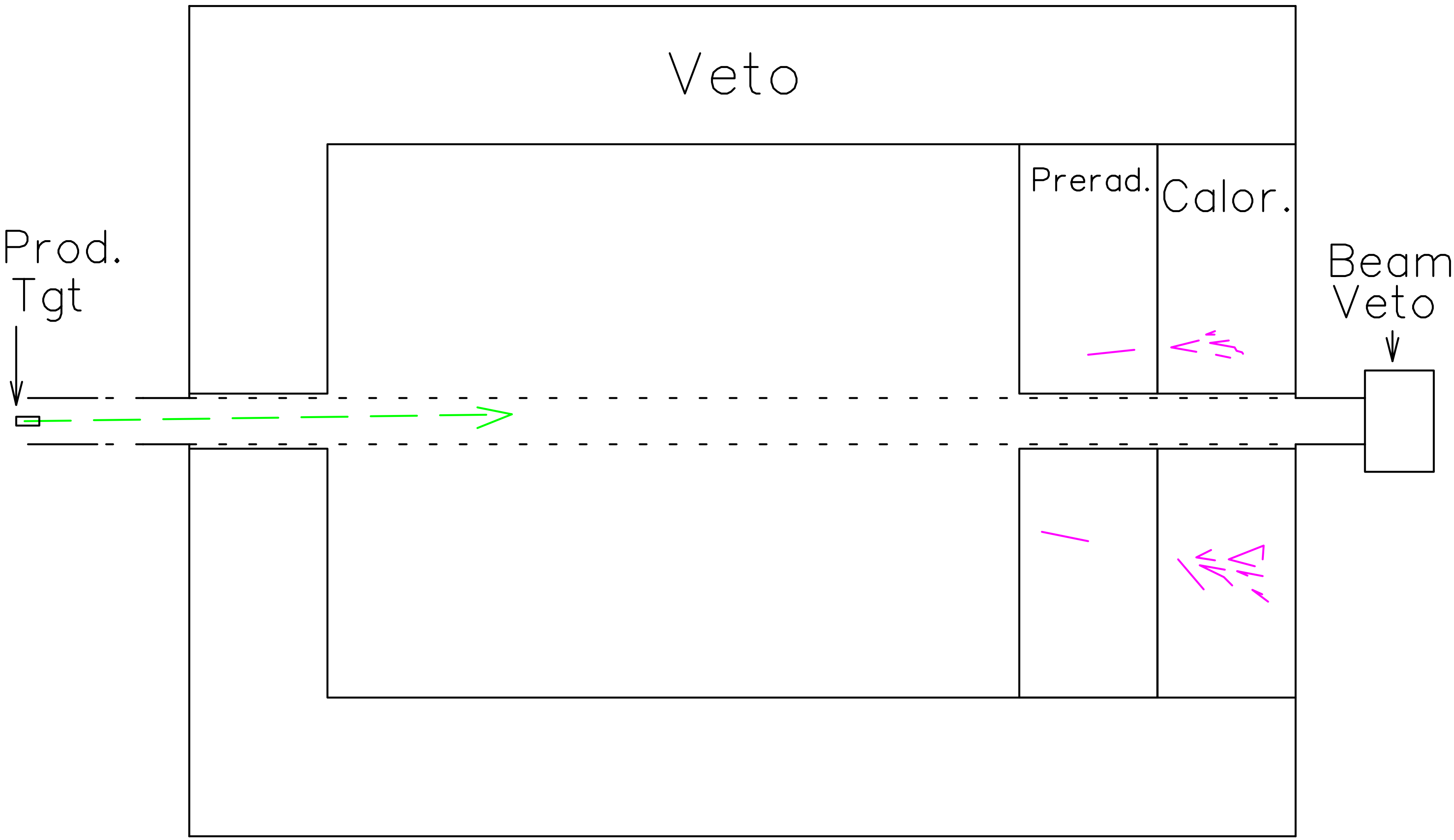
# $K_L \to \pi^0 \nu \bar{\nu}$ Experiment



# $K_L \rightarrow \pi^0 \nu\bar{\nu}$ Experiment

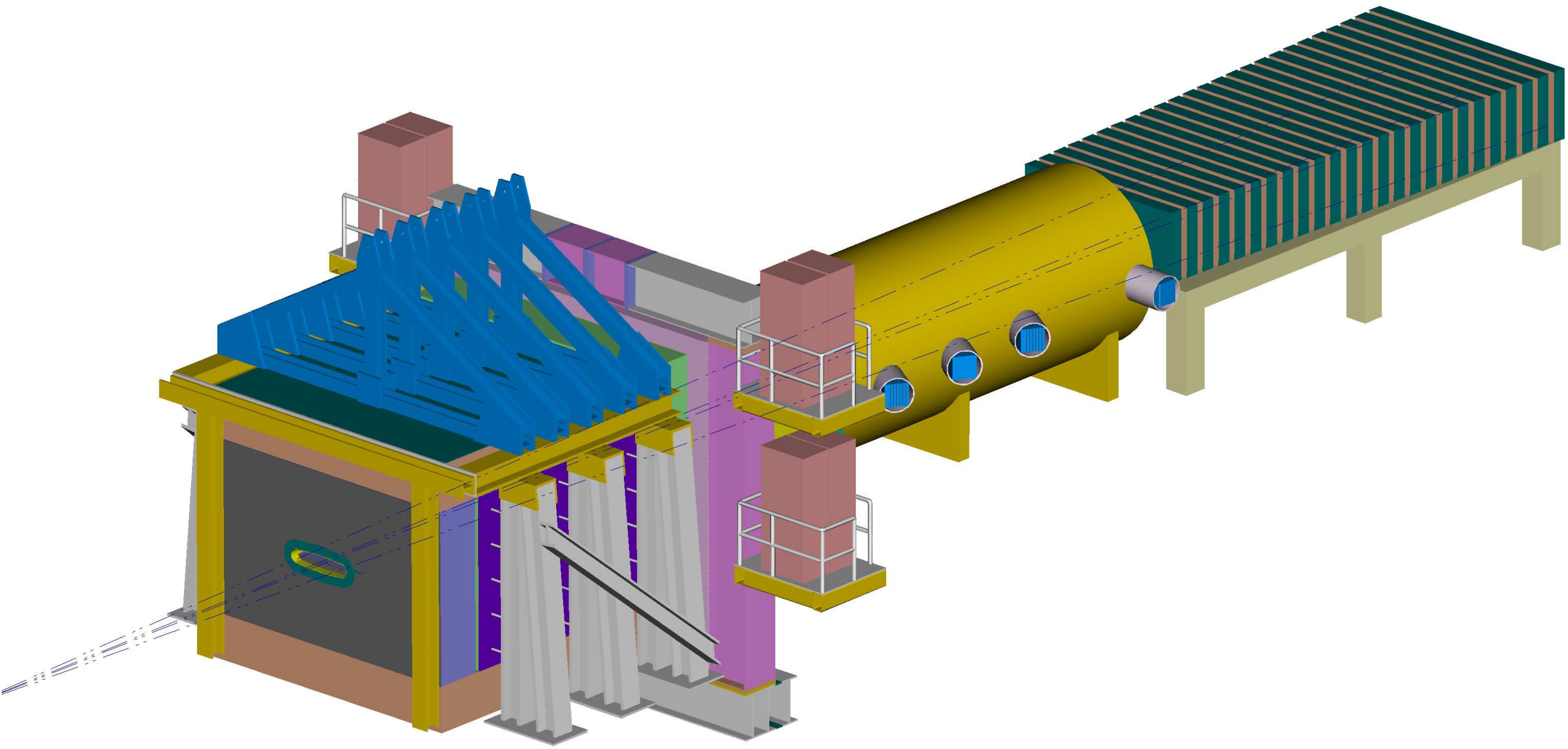


# $K_L \to \pi^0 \nu \bar{\nu}$ Experiment



Kopio

BNL, Cinncinnati, INR-Moscow, KEK, Kyoto, INFN-Perugia, Stony Brook, TJNAF, TRIUMF, British Columbia, New Mexico, Virginia, Virginia Tech, Yale, Zurich



# KOPIO $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Proposal recommended by National Science Board
- NSF-funded R&D has begun

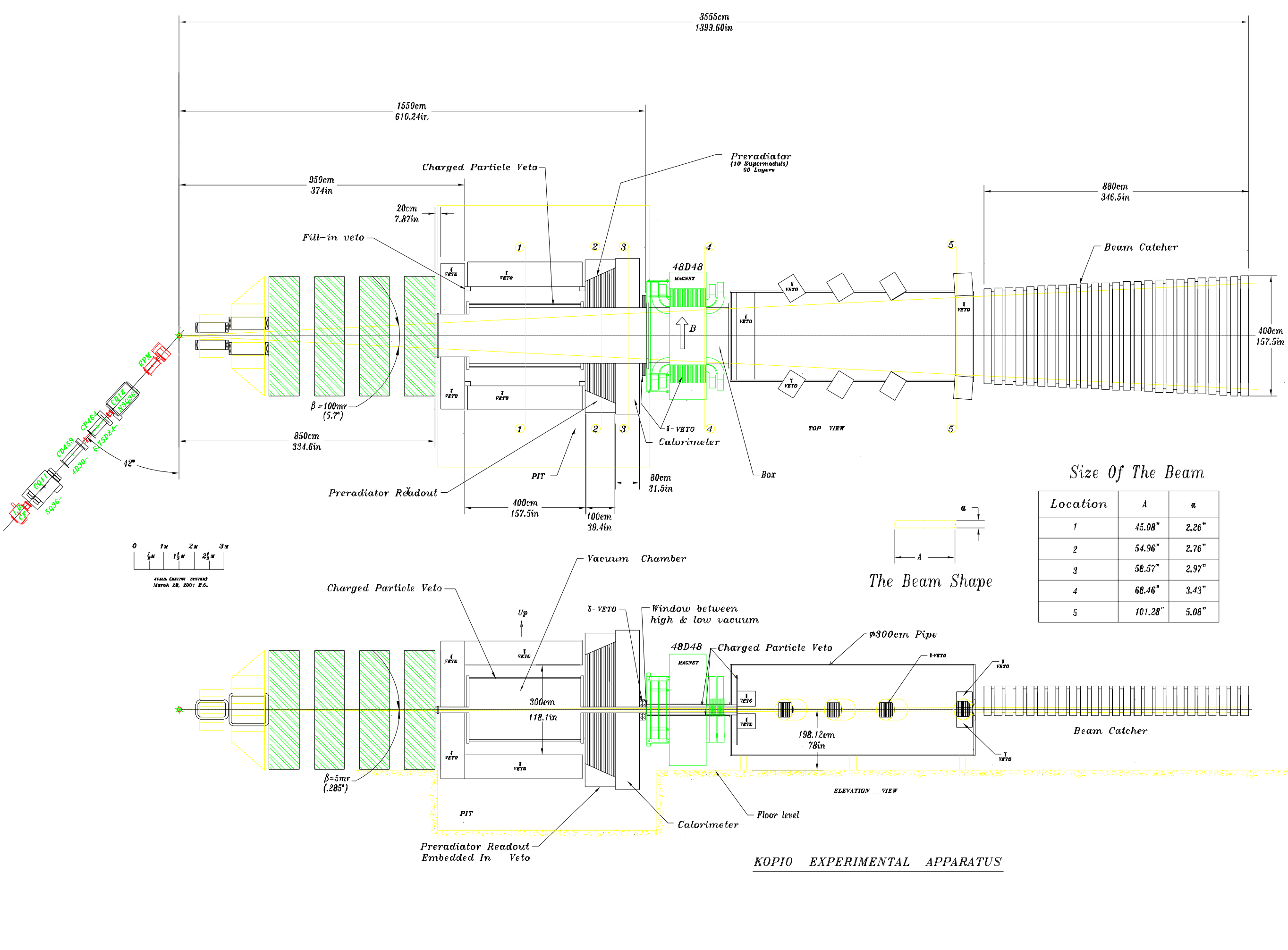
Uses the BNL AGS $\sim 20$ hrs/day it's not serving RHIC

Microbunched, low energy beam allows TOF determination of $p_K$

Measures photon direction as well as energy, time, position

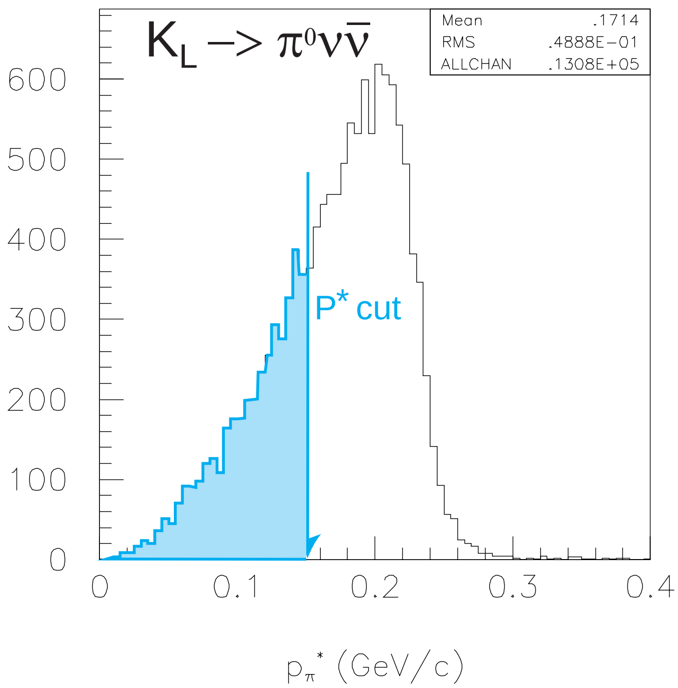
Hermetic veto with proven level of inefficiency

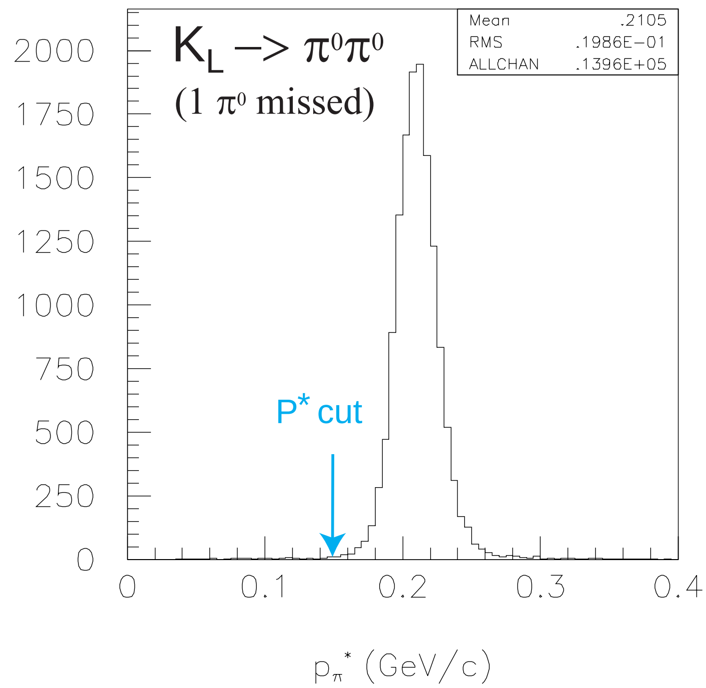
$\sim 50$ events, S:B $\sim 2:1$

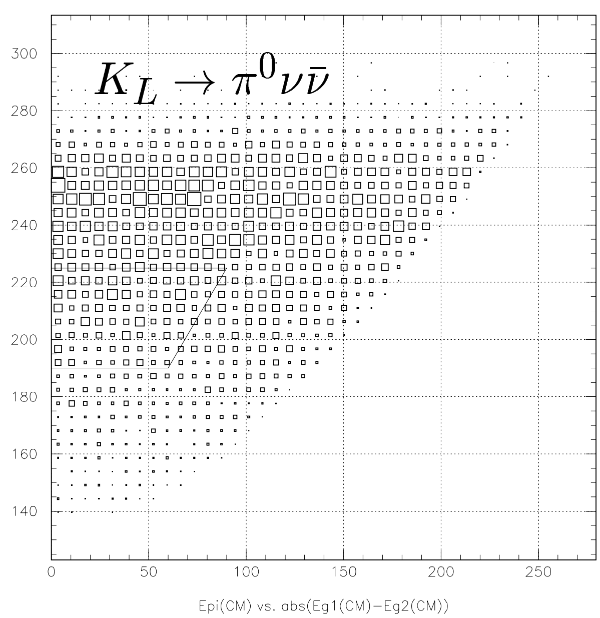


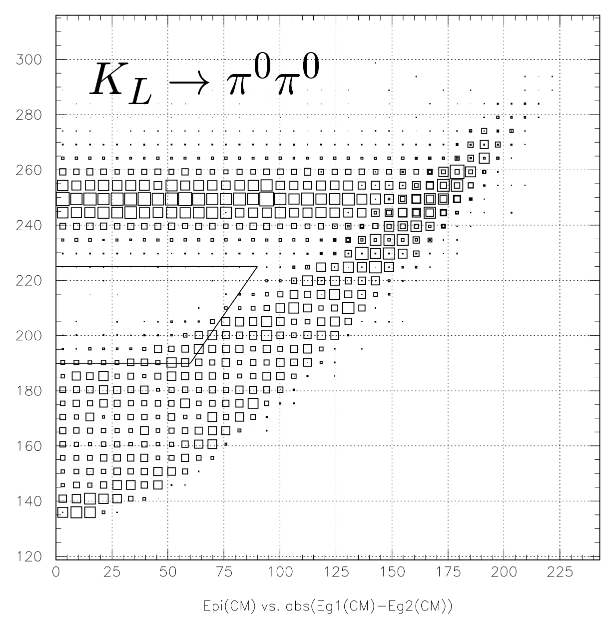

| Location | A | α |
|---|---|---|
| 1 | 45.08" | 2.26" |
| 2 | 54.96" | 2.76" |
| 3 | 58.57" | 2.97" |
| 4 | 68.46" | 3.43" |
| 5 | 101.28" | 5.08" |

# $K_L \to \pi^0\nu\bar{\nu}$ and $K_L \to \pi^0\pi^0$ identification



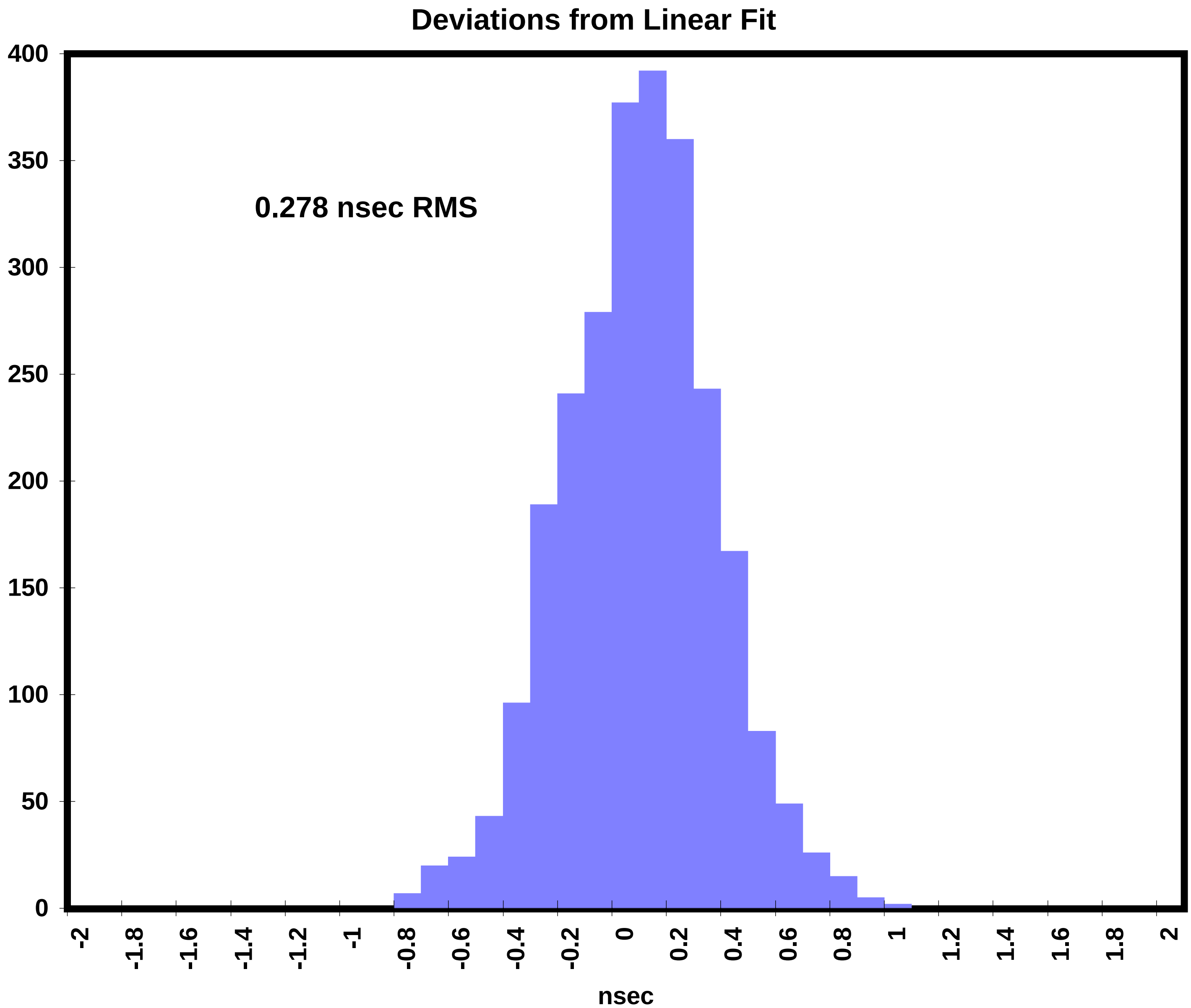



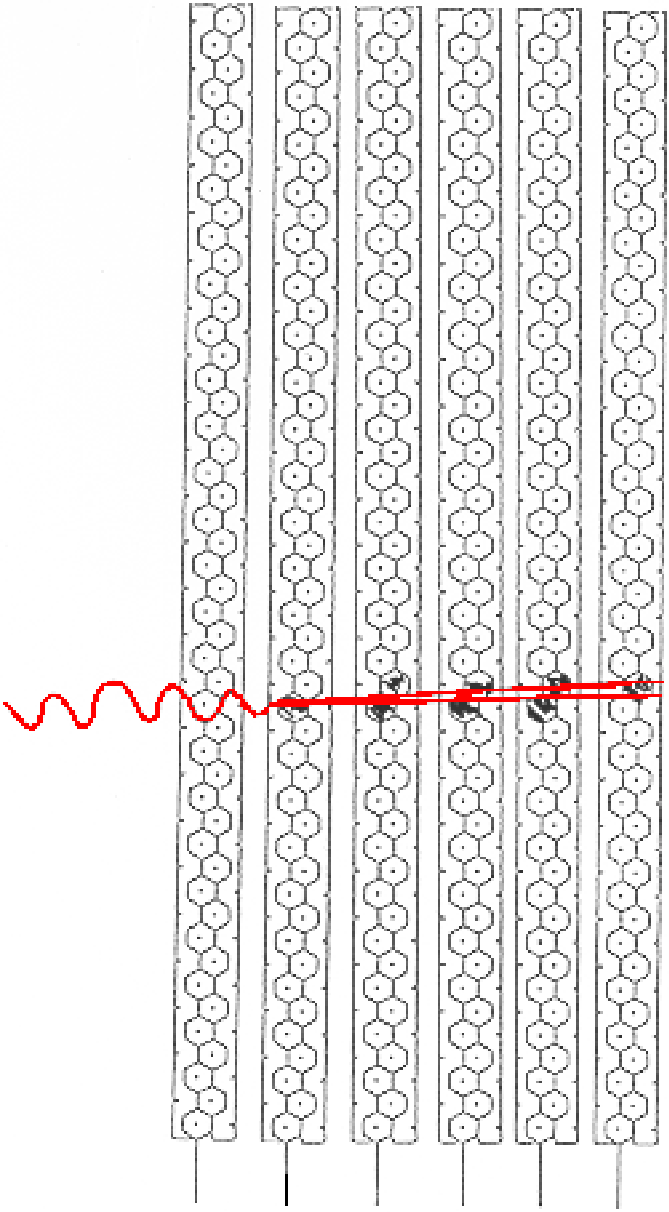




Energy of the purported $\pi^0$ (vertical) vs absolute value of the difference of the energies of the two detected $\gamma$'s (horizontal) both in the $K_L$ cm system.

# Test of microbunching on extraction at AGS




Technique now well established
Very successfully used to smooth AGS spill



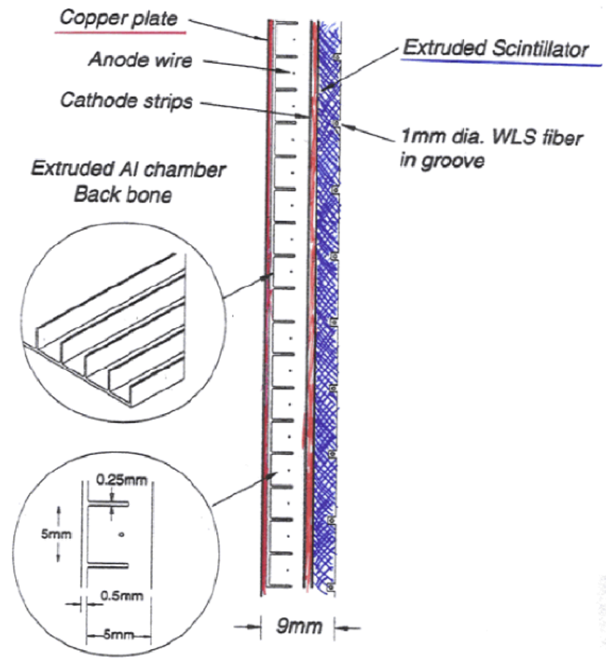
# Photon angle measurement

Principle: track 1st converted pair
in low-density preradiator

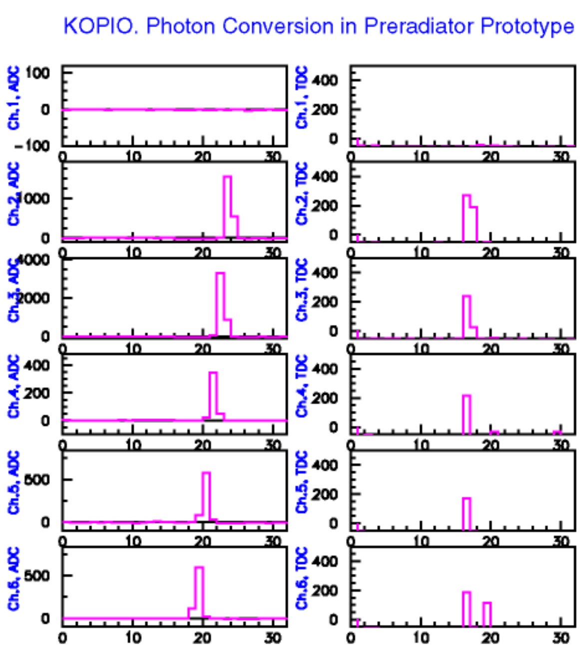
64 layers of chamber + scintillator
- each station $0.03X_0$

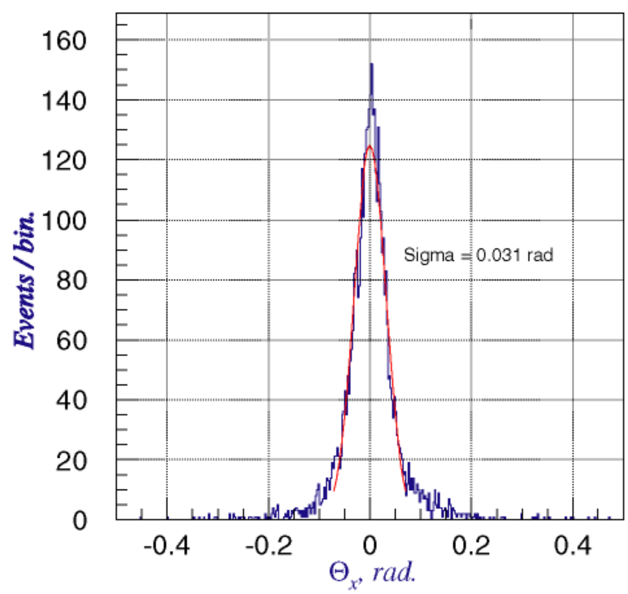
We will need $\sigma_\theta \sim 30$mr

MC indicates this can be done




Prototype tests in the LEGS tagged $\gamma$ beam at the BNL NSLS confirmed this:




$\Theta_x$ distribution of detected photons. $E_\gamma = 150$ MeV.

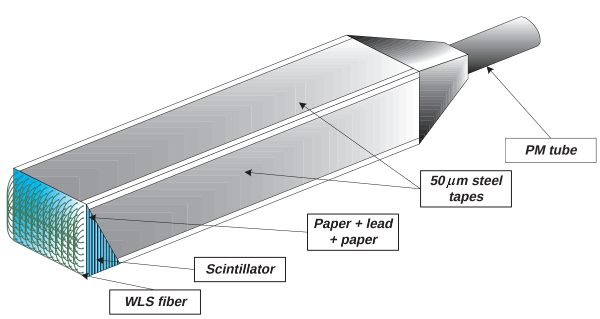
# Calorimeter

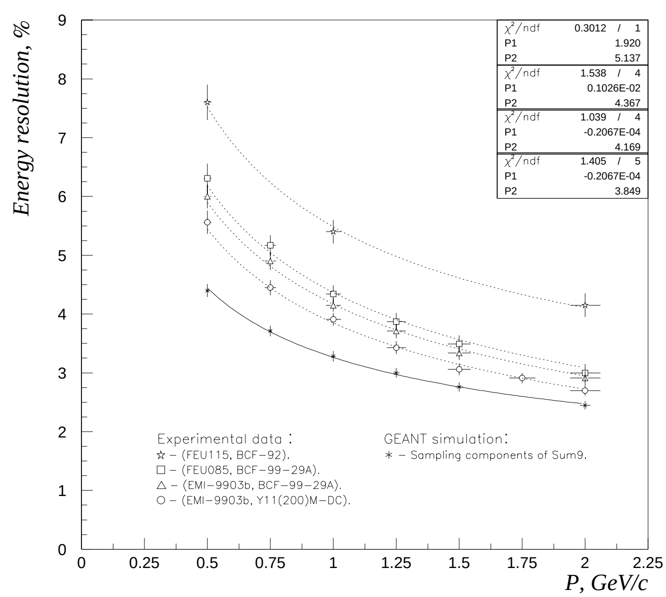
Need $\sigma_E/E \propto 0.03/\sqrt{E}$

Use well-understood shashlik technology

Better than $0.04/\sqrt{E}$ already demonstrated

MC indicates goal can be straightforwardly reached



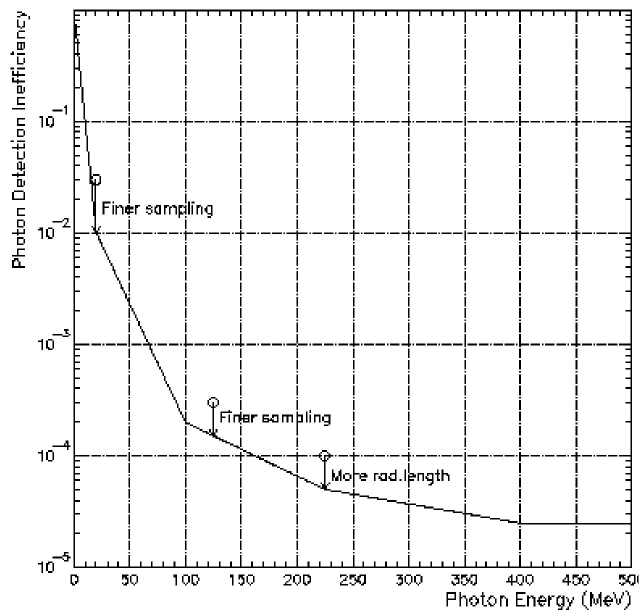

Note that **overall** $\sigma_E$ depends strongly on preradiator

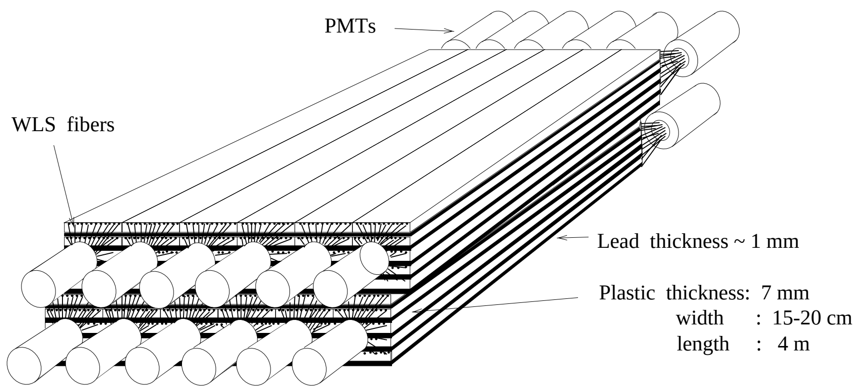
- MC of latest configuration indicates $\sigma_E/E \sim 0.027/\sqrt{E}$

# KOPIO Photon Veto

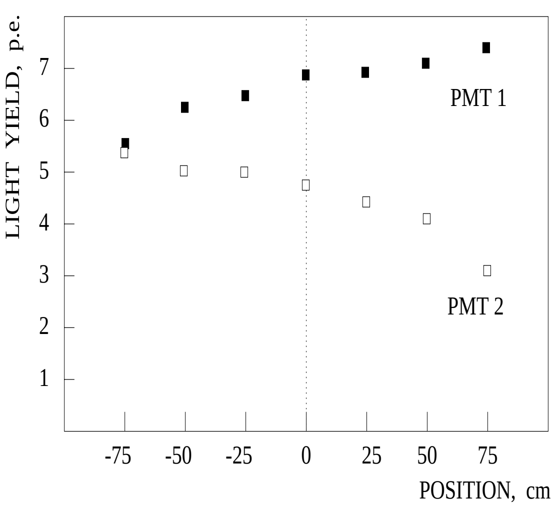
Require photon veto inefficiency only a little better than that already demonstrated in E787.

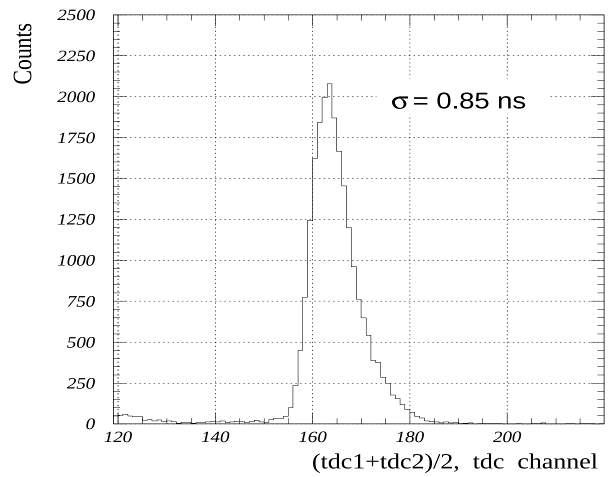
Technology similar, but wls readout gives better uniformity, brightness, and KOPIO will have more radiation lengths.




Prototype scintillators show required brightness, uniformity and time resolution:



# $\underline{K_L \to \pi^0 \ell^+ \ell^-}$

These decays also sensitive to $Im V_{ts}^* V_{td}$

At first sight much more tractible than $K_L \to \pi^0 \nu \bar{\nu}$

But they suffer from a number of problems, both experimental and theoretical

In addition to $B\left(K_L \to \pi^0 \ell^+ \ell^-\right)_{dir}$ there are 3 problematical contributions:

1. Background from $K_L \to \gamma\gamma\ell^+\ell^-$
   $\sim 10^{-5}\times$ larger than $K_L \to \pi^0 \ell^+ \ell^-$
   Even with very good resolution very hard to fight,
   already seems to be appearing in signal boxes

2. CP-conserving $2\gamma$-mediated state
   Roughly comparable in size to CP-violating piece
   Information on $K_L \to \pi^0 \gamma\gamma$ relevant
      New data from NA48
   But not so easy to make the connection
   F. Gabbiani & G. Valencia hep-ph/01005006
      absorptive contribution model dependent
      + large uncertainty in dispersive contribution

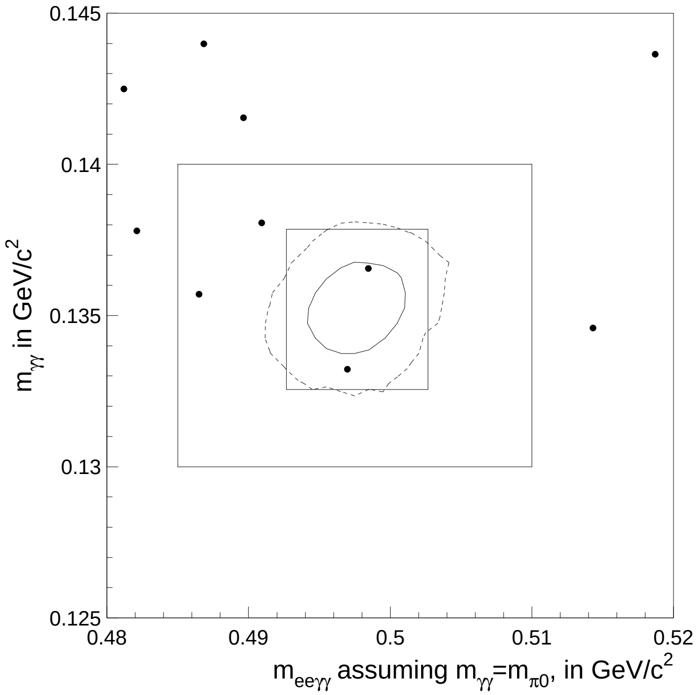
3. State-mixing CP-violating contribution $\propto |\epsilon|^2 B\left(K_S \to \pi^0 \ell^+ \ell^-\right)$
   Best knowledge is of $B\left(K_S \to \pi^0 e^+ e^-\right)$, $< 1.6 \times 10^{-7}$ (NA48)
   This yields $B\left(K_L \to \pi^0 e^+ e^-\right)_{indir} < 4.8 \times 10^{-10}$
   Still probably $100\times$ larger than actual effect
   To make life even more interesting, there's interference

Is there a way out of this morass?

# KTeV $K_L \to \pi^0 \ell^+ \ell^-$

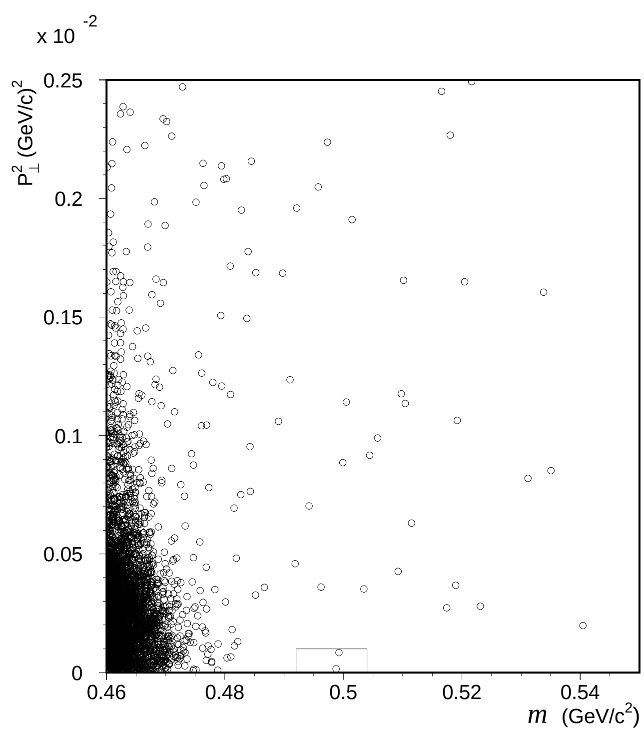
$B(K_L \to \pi^0 e^+ e^-) < 5.1 \times 10^{-10}$

Main background:
$K_L \to \gamma\gamma e^+ e^-$




$B(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$

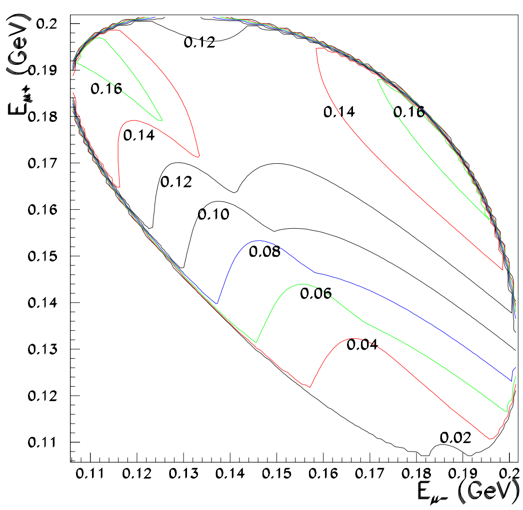
Main backgrounds:
$K_L \to \gamma\gamma\mu^+\mu^-$
$K_L \to \pi^0\pi^+\pi^-$
$K_L \to \pi^\pm\mu^\mp\nu\ +\ 2$ accid $\gamma$




Near term prospect: $\sim 2.5\times$ more data
- but background already closing in.

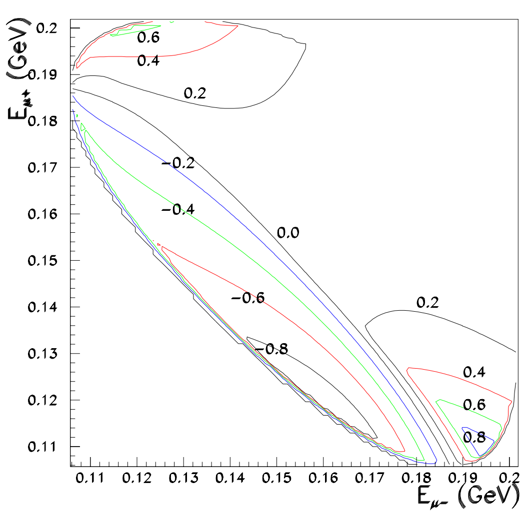
# $\pi^0\mu^+\mu^-$ Summary

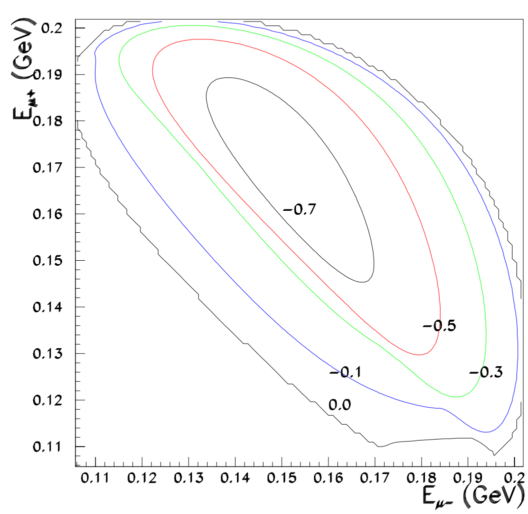
- The parity-odd observable $P_L$ has the interesting property of being sensitive to Direct-CPV.
- Both out-of-plane polarization and the lepton energy asymmetry are sensitive to indirect CP.
- Could all three measurements and the branching ratio be used to obtain the direct component ?
- Still need to examine how well the decay is described in terms of $a_s$, $\alpha_V$, and $Im(\lambda_t)$.




Decay distribution

Longitudinal and out-of-plane polarizations



# Future for Rare Kaons

Near term:

- AGS-E949 $K^+ \to \pi^+ \nu \bar{\nu}$ to $\sim 10^{-11}$/evt
  - is high BR as high as E787 level?
- KEK-E391a 1st dedicated $K_L \to \pi^0 \nu \bar{\nu}$ experiment
  - pilot for JHF experiment
- NA48/1 and /2
  - Rare $K_S$ decays
  - $K^+ \to 3\pi^{\pm}$ CP-asymmetry

Medium term:

- CKM - $K^+ \to \pi^+ \nu \bar{\nu}$ to $\sim 10^{-12}$/evt
- KOPIO - $K_L \to \pi^0 \nu \bar{\nu}$ measure $Im\,(\lambda_t)$ to 10%
- Very interesting comparisons with $B$ sector

Long term:

| Facility | $E_p$ (GeV) | p/sec | $0.7\,GeV/c\;\;K^+$ | $45^o\,K_L$ | $K_L$ (fw d.) |
|---|---|---|---|---|---|
| BNL AGS | 24 | $3 \times 10^{13}$ | 1. | 1. | 1. |
| FNAL MI | 120 | $10^{13}$ | 0.51 | 0.47 | 1.68 |
| JHF | 50 | $6 \times 10^{13}$ | 2.12 | 2.23 | 3.74 |
| CERN $\mu$SR | 24 | $10^{15}$ | 30. | 30. | 30. |

# Conclusions

LFV experiments have been pushed to remarkable sensitivities
- correspond to mass scale of well over 100 TeV

**But** success has killed most models predicting LFV in $K$ decay
- future mainly as by-products of other studies

High precision measurement of $K_L \to \mu^+\mu^-$ available
- very useful if theoretical issues resolved
- auxilliary measurements to help this resolution in process
- but situation still unsettled

$K_L \to \pi^0 \ell^+ \ell^-$ experiments have been pushed by an O.M.
- Experiments on auxillary processes have made similar progress
- But background is starting to be seen
- and progress in untangling the components slow
- Maybe new idea will help

$K^+ \to \pi^+ \nu\bar{\nu}$ has been seen,
- clear that it can be exploited
- two initiatives to pursue it further
  - $10^{-11}$/evt level experiment in testing stage
  - $10^{-12}$/evt level experiment in R&D phase

First dedicated experiment to seek $K_L \to \pi^0 \nu\bar{\nu}$ proceeding
Initiative to go all the way in progress
- trying for $\sim 10\%$ measurement of $\eta$

Goal is future high precision determinations of $\lambda_t$ from $K$'s
to be compared to $B$ information to critically test SM